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Bridge Management Systems: Extended Review of Existing Systems and Outline framework for a European System

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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.

To address this problem a project was undertaken to develop a framework for the management of bridges on the European road network The title of the project is Bridge Management in Europe (BRIME) and the objective was to develop a framework for a bridge management system that enables bridge maintenance to be optimised taking account of all factors affecting bridge management. These include: condition of the structure, load carrying capacity, rate of deterioration, effect on traffic, life of repairs and the residual life of the structure. The project is being undertaken by the national highway research laboratories in the UK, France, Germany, Norway, Slovenia and Spain and is being 50% funded by the European Commission. The remaining 50% of the UK contribution is being funded by the Highways Agency. Further details concerning the project are given in the other project deliverables and a brief overview is given on the TRL web-site (http://www.trl.co.uk/brime/index.htm)

SUMMARY

This report is divided into two parts. The first describes a review of existing Bridge Management Systems (BMS) used in Europe and abroad. The review was based on a questionnaire that was developed at the beginning of 1998 and up-dates the results reported in Deliverable D4. The second part brings together the findings from the review and the work undertaken in the rest of the project to develop a framework for a bridge management system.

The questionnaire was sent to the partners in the BRIME project and to other European countries, as well as countries outside Europe known to be well advanced in terms of bridge management (Canada, Japan and USA).

Sixteen responses were received and analysed during 1998 and 1999. The responses received from the FHWA of the United States of America were treated separately as they used different systems, namely BRIDGIT and PONTIS.

The information given in the completed questionnaires was analysed and a list of functions needed to satisfy the objectives of a bridge management system that could realistically be achieved was obtained.

These functions were developed to generate a system of well defined outputs for the BMS. The input data and algorithms needed to produce the outputs were specified and allocated to the appropriate workpackage groups providing them with clear objectives and formats.

The results of this study, along with the findings from the other workpackages were used to develop an outline framework for a European bridge management system.

IMPLEMENTATION

The results of this work will be disseminated through publication of a report on the BRIME project and a seminar will be held during the autumn of 2001 to present the findings to bridge owners, bridge engineers, consultants and other interested parties.

BRIDGE MANAGEMENT SYSTEMS: EXTENDED REVIEW OF EXISTING SYSTEMS AND OUTLINE FRAMEWORK FOR A EUROPEAN SYSTEM

1 INTRODUCTION

The objective of this project is to develop a strategy for the management of the bridge stock on the European Highway Network. This strategy will include a methodology for the development of a system for optimising the use of the resources available for the management of bridge maintenance. The specific objective of this workpackage is to specify the requirements of a bridge management system (BMS) that will satisfy the project objectives and to co-ordinate the work and combine the results from workpackages 1 to 6 to achieve these requirements.

The first aspects considered were the functions that the BMS should have. These were established by studying the literature and the results of a carefully composed questionnaire that was sent to a number of highway authorities in Europe and North America. The evidence from the completed questionnaires was analysed and a list of functions needed to satisfy the objectives, and that could realistically be achieved, was obtained.

These functions were then developed to generate a system of well defined outputs for the BMS. The input data and algorithms needed to produce the outputs were specified and allocated to the appropriate workpackage groups providing them with clear objectives and formats.

2 REVIEW OF EXISTING BRIDGE MANAGEMENT SYSTEMS

2.1 METHODOLOGY

In order to produce an outline framework for management of bridges on the road networks across Europe, a review was undertaken of existing Bridge Management Systems (BMS) used in Europe and abroad. This review was based on a questionnaire that was developed during the first months of 1998.

The questionnaire was sent to the partners in the BRIME project, and to other European countries, as well as countries outside Europe known to be well advanced in terms of bridge management (Canada, Japan and USA). In June 1998 it was sent to the following Departments of Transportation:

- France - Road Directorate (via LCPC)
- Germany - BASt
- Great Britain - TRL
- Norway - Directorate of Public Roads (via NPRA)
- Slovenia - Road Directorate of the Republic of Slovenia (via ZAG)
- Spain - CEDEX
- Denmark - Danish Road Directorate

- Finland - Finnish National Road Administration

- USA - Federal Highway Administration
  - New York City DOT
  - California DOT
- Canada
- Japan - Public Work Research Institute.

The number of replies received was excellent, since only the questionnaires sent to Japan and Canada were not returned; however, the time taken for the questionnaires to be completed was underestimated, with some responses not being returned until late October 98.

In January 1999, R. Baastians from the European Community asked for the questionnaire to be sent to other members of the FEHRL Network (Forum of European Highway Research Laboratories) in order to have a more global view on existing management practise in Europe. In April 1999 the questionnaire was sent to eleven other countries: Austria, Belgium, Croatia, Greece, Hungary, Iceland, Ireland, Italy, Netherlands, Portugal, Switzerland, and moreover Sweden.

Only five responses were obtained: Belgium (the Wallonie region), Croatia, Ireland, Portugal and Sweden.

The responses were obtained from:

D - Germany - Bundesanstalt für Strassenwesen: Dr. Peter Haardt
E - Spain - CEDEX: Rafael. Astudillo
F - France - Road Directorate: J.L. Astruc
UK - Great Britain - Highways Agency: Parish Tailor
NO - Norway- Directorate of Public Roads: Borre Stenvold
SI - Slovenia - Road Directorate of the Republic of Slovenia: Miklavz Cepon
BE - Belgium - Ministry of Equipment and Transportation of Wallonie: P. Demars
CRO - Croatia - Croatian road Administration: Vlasta Zugelj
DK - Denmark - Danish Road Directorate: Jorn Lauridsen
FIN - Finland - Finnish National Road Administration: Mrs Maria-Kaarina Söderqvist
IE - Ireland - National Roads Authority: Tom McCormack
PT - Portugal - Motorways of Portugal -BRISA: Mario Cardoso & Mrs Sonia Santos
SE - Sweden - National Road Administration: Lennart Lindblad
FHWA - USA - Federal Highway Administration: Edgar P. Small
NY - New York City DOT: Bojidar Yanev
CA - California DOT: Richard W. Shepard

Sixteen responses were therefore received and analysed. The responses received from the FHWA of the United States of America were treated separately as they used different systems, namely BRIDGIT and PONTIS.

The information obtained from the questionnaires is summarised in Table 1.

2.2 ANALYSIS OF THE REPLIES TO THE QUESTIONNAIRE

2.2.1 Global description of bridge management systems

Twelve countries operate a computerised Bridge Management System; three countries do not operate a BMS at present but are in the process of developing one (D, E and IE), and one country uses a partial one (F). For the countries operating a computerised BMS, its age varies from 2 to 22 years.

Slovenia and Ireland do not have an official user manual or guidelines although Slovenia does have a three volume report on a research project carried out by ZAG (Slovenian National Building and Civil Engineering Institute). For other countries the procedures for using the BMS are given in various documents: a maintenance manual (UK), management instructions (F) and a user manual (NO, BE, CRO, DK,FIN, PT, SE, NY). In D and E, there is no special documentation.

In most of the countries, the BMS is used to manage bridges on the National Highway Network ie motorways and all purpose trunk roads.

No country has its BMS linked to a road management system. However the Norwegian system has an automatic link to the road network for route number and location.

2.2.2 Information on the database

Most of the countries that use a computerised BMS use commercial database software; the most popular one is ORACLE as can be seen below:

SQL : FHWA, D
ORACLE : F, NO, FIN, FHWA, CA
ACCESS : F, FHWA
DELPHI : CRO, DK
POWER BUILDER : BE

The exceptions are UK, SI, and SE that do not use commercial database software.

PONTIS uses Sybase SQL Anyware as the RDBMS engine; drivers are also provided for Oracle and MS-Access. The database is ODBC compliant and runs under MS-Windows (3.1 and 95/NT).

Germany is using commercial SQL database software (SIB-Bauwerke) for recording data on structures, inspection, maintenance and cost.

France is using ORACLE for the global evaluation of the condition of bridges (IQOA software), and ACCESS for prioritising bridges for repair (OA software).

Most of the countries are working under the WINDOWS environment:

- Norway uses a client/server architecture (Windows 3.1 on a PC/ UNIX or Windows NT on a server).

- Finland uses an inventory and network BMS in DOS, and a project BMS in Windows NT.

NY and SI also use DOS.

In most countries, the database is used for both management of individual structures and management of the bridge stock. Spain and Portugal use the database mainly for management of the bridge stock, and France uses a different database for management of individual structures and for management of the stock.

The BMSs are used at all the different levels that have a role in maintenance ie national, regional offices or county authorities and maintaining agents. In Norway, Denmark and Sweden it is also used by consultants, and in Sweden it is also used by technical universities and contractors. The responsibility for maintenance is always at the national level (Road Directorate).

Information is updated according to the type and performance of the BMS; for some it is done daily, some occasionally and for others annually or even every 2 years.

The number of datafields varies enormously; for example the Norwegian database contains 1228 fields in 147 different tables. The Finnish database contains 250 datafields. Some databases have the facilities to add user-defined fields.

2.2.3 Bridge condition

There are 3 or 4 levels of inspection (routine, general, detailed and special). In general, the results of general and detailed inspections are stored on the database. Norway and Sweden also store the results of measurements and investigations.

The condition of bridges is also stored, except in the UK, E and CRO. In general the condition is stored for individual elements and the whole bridge, except in D where the condition is stored only for the whole bridge. The condition is mostly based on a 3 to 5 rating scale.

In Sweden bridge condition is recorded according to three types of condition:

- the physical condition based on measurements related to development of previous or new damage, degradation processes, pollution processes, etc
- the functional condition stated in terms of 4 classes: defective at the time of inspection, defective within 3 years, defective within 10 years, defective beyond 10 years;
- the economic condition described in terms of quantity and cost of a remedial activity (cost is calculated automatically).

2.2.4 Other Information recorded on BMS

The date, type, cost and location of maintenance work are recorded in every country. In France, it is only stored for maintenance work which costs more than 300kF (46kEuro) and for Slovenia, type and cost are stored separately.

The condition immediately before and after maintenance is not stored, except in BE, CRO, DK, PT and CA.

2.2.5 Prediction

Most countries do not use past condition data or a deterioration model to predict future condition. The exceptions are:

- FIN which uses probabilistic Markovian models at the network level, and deterministic models at the project level.

- BE, SE and NY which use past condition data and degradation of materials with time.

- CA which uses past condition data.

- F and SI use previous condition ratings.

DK does not believe in models for predicting future condition.

2.2.6 Information on costs

Table 2 gives some information on costs. In most countries the BMSs are used to store maintenance, repair and, in some cases, inspection costs; the exceptions are BE, CRO, D, IE, NO, PT, and SI.

The BMSs used in most countries do not calculate the financial consequences of traffic disruption caused by maintenance work and the associated traffic management costs. In Sweden, the object planning module of the system contains a model for calculation of road user costs; this model includes time and vehicle costs. In UK, delay costs are calculated using either look-up tables or the computer programme QUADRO.

2.2.7 Decision on maintenance and repair

Most countries do not use the BMS to make decisions on maintenance and repair. The exceptions are DK which uses a prioritisation programme, FIN which uses a repair index, SE which chooses from alternative strategies, the option with the lowest current value (based on a 4 % discount rate), and CA which uses long term lowest cost optimal strategies from PONTIS.

In F, D, BE and IE, decisions are based on engineering judgement. UK uses cost benefit analysis. E makes a decision based on the cost of the repair as a percentage of replacement costs but it is not clear from their response whether this includes the traffic disruption costs.

Most countries decide when maintenance work is needed on the basis of inspections and engineering judgement. SI Decides on the basis of increased traffic flows and the importance of the bridge to the region. CA decides on the basis of safety and an analysis of the economic benefits. (In general it is based on technical rather than economic requirements.)

Most countries decide which is the best maintenance option to use on basis of engineering judgement. In SE and UK, it depends on the solutions available and the cost of traffic management and traffic disruption; whole life costing is also used for major schemes.

In SI it depends on the importance of the bridge, and FIN uses repair guidelines. CA uses long-term optimal strategies.

2.2.8 Prioritisation

D, F, UK, NO, SI, BE, CRO, IE and PT do not have a BMS module for generating an optimal (minimum cost) maintenance strategy subject to certain constraints such as a lowest acceptable level of condition. Such a module is used in DK (for repair) and E, FIN, SE, NY and CA.

In the optimisation process, other constraints are usually applied such as cost and policy for UK, and for CA it is the “ lowest long-term cost that prevents failure ”. For SE, the “Lack of Bearing Capacity” and the “Lack of Capital Value” are the two parameters used to describe the performance and economic conditions of bridges in the prioritisation process. Budget and bridge condition are also mentioned by several countries as a normal constraint.

In F, D, UK, NO, SI, BE, CRO, IE, and PT, the BMS does not produce a prioritised maintenance strategy for the bridge stock when the maintenance budget is insufficient. However it does in E, DK, SE, NY and CA, although in DK this is only done for repair.

No country quantifies the consequences of carrying out a sub-optimal maintenance strategy. DK, SE and NY calculate the economical consequences of not carrying out an optimal maintenance strategy.

Each country uses different criteria for prioritisation (Table 3)

In most countries, the responsibility for prioritisation of bridges is at the national level. Only in NO, FIN and SE is the responsibility at the local (or regional) level.

2.2.9 Quality control

There is no quality control of bridge management in any country except FIN where internal procedures are applied and SE where some tools control the quality of data.

2.3 BMS IN THE UNITED STATES OF AMERICA

Design, assessment, repair, and strengthening of bridges are increasingly important topics in the effort to deal with deteriorating infrastructure in the United States. About one-third of the nation’s 570,000 bridges are classified according to FWHA criteria as deficient and in need of rehabilitation or replacement. The major factors that have contributed to the present situation are age, inadequate maintenance, increasing load spectra, and environmental contamination. The cost of the bridge replacement and rehabilitation program is estimated at about 70 billion ECU.

Bridge management in the USA is performed by the bridge owning agencies. These are typically the State Departments of Transportation, County Agencies and Metropolitan Areas. There is no requirement for a particular BMS to be used and there are three systems currently in use:

- **PONTIS:** the predominant system used in the US, and licensed by 39 States.
- **BRIDGIT**: A project level system employed in the State of Maine and used by Washington State and Louisiana.
- **State Specific Systems**: five states have developed their own BMS: Alabama, Indiana, New York State, North Carolina and Pennsylvania.

2.3.1 Description of BRIDGIT

As described in NCHRP 300, the objectives of BRIDGIT are to " assist decision makers at all bridge management levels to select optimum solutions from an array of cost effective alternatives for every action needed to achieve the desired levels of service within the funds allocated and to identify future funding requirements ". The main functions of BRIDGIT are to provide support for the transportation investment plan, and for project level planning and programming.

The system maintains a comprehensive data model to evaluate the condition states of bridges (including functional deficiencies), determine policies for optimisation of funds at network level, recommend project level action, and prioritise maintenance and repair actions.

The database engine is FoxPro/Visual FoxPro. The information is used for both the management of a stock of bridges and the management of individual structures. The users of the database are the bridge maintenance engineers.

National Bridge Inventory (NBI) fields and element models are both included in the BMS, but element inspections (more detailed) are performed to replace the NBI condition rating inspection which is too general. Inspection data is updated every 2 years. Fracture critical inspections, under water inspections and other special inspections are performed periodically on vulnerable structures (between 6 and 48 months according to site specific conditions). Visual inspection techniques are used with a 3 to 5 scale rating system. All bridge information collected over time is stored in the system.

The BMS records the date, type and cost of work performed both per bridge and per element. It also records the condition of bridges before and after the maintenance work is performed.

For predicting future condition, BRIDGIT uses Markovian deterioration models where the future condition state depends on a transition probability matrix formed using the optimal policy. Actual condition state models are used for updating the probabilities that condition states will change in the future, and predictions of future load carrying capacity are based on the worst superstructure element condition.

BRIDGIT stores the direct and indirect costs of maintenance and repair work but not inspection costs. It includes the financial costs of traffic disruption, and user costs due to accidents, increased travel time and increased travel distances associated with detours. These costs are estimated on a bridge by bridge basis.

The bridge level actions are developed through minimising expected life-cycle costs over a 20 year planning horizon. The optimal sequence of actions and the optimal time to take action are considered. Benefits are calculated as user cost savings.

Prioritisation and project planning are performed using an incremental cost benefit analysis. This procedure is capable of developing a minimum cost strategy for a given budget. Moreover, condition state distributions can be generated to examine and quantify the effects on condition of following a sub-optimal policy.

2.3.2 Description of PONTIS

PONTIS has the same functions as BRIDGIT plus the following additional features:

It uses a relational database and Sybase SQL Anyware for the engine. Drivers are also provided for Oracle and MS-Access. The database is ODBC compliant and runs under MS-Windows.

The overall condition is predicted using a health index for performance measurement. The future health of the inventory may be predicted based on the size of the budget.

The optimisation is based on a network level using the minimum expected life-cycle costs over an infinite planning horizon. Benefits are computed as agency cost savings of performing an action compared with postponement of the action by one year. The optimal policy is then applied to one bridge and aggregated to determine the optimal maintenance strategy for each bridge. The best maintenance option is the minimum cost option for each element; the best bridge-level option is dependent on the costs and benefits.

The procedure for prioritisation develops a minimum cost policy constrained to prevent element failure. The models may be easily accommodated to consider minimum conditions or a threshold health index.

In general, PONTIS is used by bridge maintenance engineers (for inspection, in-service analysis, design), planners (long-term planning, corridor planning, etc.) and upper level decision makers (budgeting and forecasting).

The Pontis BMS can generate a large number of graphical and tabular reports and may be customised through any SQL query software.

Main Functions of BMS	**D**	**DK**	**E**	**F**	**UK**	**NO**	**FIN**	**SI**	**CA**	**NY (state**
Name	SIB-Bauwerke	Danbro		Edouard and OA	NATS	Brutus				
Time of operation (years)	New	20			15	2	3	5		4
Number of bridges managed	34,600	1,400	15,000	22,000	9,500	17,000	15,000	1,760	25,000	10,000
Inventory of existing stock	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Schedule of inspection	Yes	Yes		Yes	Yes	Yes	Yes		Yes	Yes
Condition of structures (rating, ...)	Yes	Yes		Yes	Yes	Yes	Yes	Yes	Yes	Yes
Bid for maintenance funds	No	Yes		Yes	Yes	Yes	?		Yes	Yes
Prioritising of maintenance work	No	Yes		Yes	Yes	Yes	?	Yes	Yes	Yes
Budget planning (long term)	No	Yes		No	Yes	Yes	Yes			Yes
Registering detailed cost information for actions	Yes	Yes		Yes						Yes
Safety assessments	No			No	Yes					Yes
Taking into account alternative maintenance strategies	No			No	Yes					Yes
Application of whole life costing	No			No	Yes					Yes
Road user delays	No			No	Yes					
Deterioration prediction	No	No	No	No	No	No	Yes	No	Yes	Yes

Table 1 Information on BMS

Main Functions of BMS	**BE (Wallonie)**	**CRO**	**IE**	**PT**	**SE**
Name	BDOA		Project...		SAFEBRO
Time of operation (years)	22	2		3	12
Number of bridges managed	5 000	1 200	> 1 800	1 400	15 000
Inventory of existing stock	Yes	Yes		Yes	Yes
Schedule of inspection	Yes	Yes		Yes	Yes
Condition of structures (rating, ...)	Yes	Yes		Yes	Yes
Bid for maintenance funds	Yes	Yes		Yes	Yes
Prioritising of maintenance work	Yes	Yes		Yes	Yes
Budget planning (long term)	No	No		No	Yes
Registering detailed cost information for actions	No	No		No	Yes
Safety assessments					Yes
Taking into account alternative maintenance strategies	No	No		No	Yes
Application of whole life costing	No	No		No	No
Road user delays	No	No		No	Yes
Deterioration prediction	Yes	No		No	Yes

Table 1 (continued) Information on BMS

Information on costs (millions of ECU)	**D**	**DK**	**E**	**F**	**UK**	**NO**	**FIN**	**SI**	**CA**	**NY City**
Total surface of bridges (million of m^2)	24			8.1				0.7		1.4
Number of bridges managed	34 600	1 400	13 600	22 000	9 500	17 000	15 000	1 760	25 000	847
Inspection cost	3	nd	nd	4.6	15	nd	1.2		4.5	nd
Routine maintenance cost		nd	nd	11.5	15	nd		0.43	4	20
Specialised maintenance cost	270	nd	nd		97.5	nd	2.6		6	20
Repair and strengthening cost		nd	6	28.6	90	nd	10.2		100	20
Replacement cost	45	nd	nd	3.1	7.5	nd	10.2	13.6	50	450
Total cost (annual)	318	nd	13	47.8	225	37	29.8	14	200	510
Replacement value of the stock	30 000	2 600	4 100	12 310	22 500	6 000	2 890	nd	nd	6 000
Total cost of maintenance/replacement value	0.4 %		0.3 %	0.4 %	1.0 %	0.6 %	1.0 %			8.5 %
Mean maintenance cost per bridge	0.009		0.001	0.0022	0.0237	0.0022	0.0020	0.0080	0.008	0.602
Mean maintenance annual cost per m2 (ECU /m^2)	13.2			5.9						365

Table 2 Information on costs

Information on costs (millions of ECU)	BE (Wallonie)	CRO	IE	PT	SE
Total surface of bridges (million of m^2)	2.656	0.520			
Number of bridges managed	5 000	1 200	> 1 800	1 400	15 000
Inspection cost					
Routine maintenance cost					
Specialised maintenance cost					
Repair and strengthening cost					
Replacement cost					
Total cost (annual)	(*)		2.5		92.1
Replacement value of the stock	3 800	330	450	860	5 300
Total cost of maintenance/replacement value			0.6 %		1.7 %
Mean maintenance cost per bridge			0.0014		0.006
Mean maintenance annual cost per m^2 (ECU /m^2)					

Table 2 (continued) Information on costs

(*): The figure cannot be obtained because funding is allocated locally for maintenance of roads and bridges

COUNTRY	CRITERIA FOR PRIORITISATION
D	Condition of Bridges Degree and consequences of damage Importance of roads Bridge Deck clearance Traffic safety Available staff
DK	Minimisation of the maintenance costs
E	Not mentioned
F	Condition of the bridges Importance of roads Minimum funds allocated for each local county Possibility for each county to do the job (studies and repairs) Policy
UK	Whole cost life Safety index Policy
NO	Degree and consequence of Damage Investigation of alternative strategies in terms of technical choices and comparison between maintenance cost (direct and indirect costs) and bridge's replacement value.
FIN	Repair Index (based on damage class of the structural parts and repair urgency class of the damages).
SI	Rating of the structure Importance of the road Load carrying capacity
BE	Risk for the stability of the structure
PT	Condition of bridges Extent and consequences of damages Traffic safety Minimisation of the maintenance costs
SE	Marginal return from choosing the more expensive strategy Calculation of the profitability of an action in year 1 compared with one year later (and same process for year 2, 3, 4 and 5) Profitability factor
CA	Benefit cost ratios
NY	Not mentioned

Table 3 Criteria for prioritisation

2.4 CONCLUSION

This review shows a wide variety of approaches in the different European countries. Most the countries use a computerised BMS. The condition of the bridge (based on bridge inspection results), information on maintenance work and costs are recorded. Prediction models that take account of indirect costs are not very well developed. Decisions on maintenance and repair, as well as prioritisation, are essentially a matter of engineering judgement.

The most advanced BMS software is PONTIS which is used by almost 40 states in USA. It is difficult to know if all the functions of PONTIS are actually used in the field, but it appears that American maintenance engineers are more prone to rely on computerised tools, than European engineers who prefer to rely on human judgement. There are some exceptions particularly in the Nordic countries such as Denmark which uses DANBRO and Sweden which uses SAFEBRO.

The findings from the questionnaire have been used to compile a list of functions needed to satisfy the objectives of a BMS.

3 FRAMEWORK FOR A BRIDGE MANAGEMENT SYSTEM

3.1 BACKGROUND

This section brings together the findings from the other workpackages to develop a framework for a bridge management system.

A bridge management system has as its heart a relational database for storing all the information required to carry out the management functions; this is called the bridge inventory. Much of this data already exists albeit in paper records. However, it should be appreciated that a considerable effort is required to compile and verify this existing data, collect missing data and thereafter to enter data modifications promptly to ensure that the data base provides a reliable and up to date record. The main functions of the BMS are best catered for in separate modules that are attached to each other via the inventory. These modules consist of mathematical models, algorithms and data processing tools. The modules needed to manage bridge maintenance efficiently and effectively have been discussed in previous workpackages and are:

- condition appraisal (Workpackage 1)
- assessment of load carrying capacity (Workpackage 2)
- rate of deterioration (Workpackage 4)
- assessment of load carrying capacity of deteriorated structures (Workpackage 3)
- deciding maintenance strategies and methods (Workpackages 5 & 6)
- prioritising maintenance work (Workpackage 6)

The modules also correspond with the main activities associated with managing bridges:

- various types of inspection
- testing
- assessment of bridges in different conditions
- preventative maintenance
- repair work
- strengthening
- replacement

Management systems sometimes exist for road pavements, lighting columns, retaining walls and embankments and street furniture such as sign gantries and signposts. In theory all these elements of road infrastructure could be combined to form an all embracing infrastructure management system which would have some potential benefits. At the present time, however, it is considered that significant operational difficulties would arise because the operations at the site level are not yet sufficiently well integrated. The approach taken here is to produce the framework of a management system for bridges while taking account of the long-term objective of combining this with management systems for other types of infrastructure. The first step to full integration would be to link the inventories for different types of infrastructure through their location on the road network using GPS.

The application of these modules generates a maintenance programme that indicates:

- the maintenance work needed each year on each bridge in the stock and
- the recommended maintenance method and its estimated cost

that are necessary to keep all the bridges in the stock open to the full range of normal traffic at a minimum overall lifetime cost subject to any constraints that may be imposed from time to time such as a maximum annual budget for maintenance work. Where it is necessary to impose constraints the BMS should evaluate the consequences of imposition in terms of reduced life, increased lifetime cost and increased disruption to bridge users. The following sections discuss the background to each module and summarise the work described in previous workpackages before describing the BMS framework and interconnections between the modules. Particular attention is given to the data requirements of each module and to applications at both network and project levels.

3.2 GENERAL APPLICATIONS OF THE BRIDGE INVENTORY

Typically bridge inventories contain a few hundred data fields which cover aspects such as:

- bridge identifiers - name / number
- bridge location - map reference, road name, route number, obstacle crossed
- bridge elements and components
- bridge dimensions
- bridge materials
- forms of construction
- year built and required life
- traffic data
- load assessment history
- inspection history
- test history
- maintenance history
- bridge owner, maintenance agent, region, services

Queries and associated reports relating to this data can be carried out using normal database operations. An almost unlimited variety of queries can be posed using logical operators and criteria on selected data fields. A few examples of queries follow which will illustrate the possibilities:

Example 1: List the name, bridge number and age of all bridges in region A where the principal bridge inspection is overdue by more than 1 year.

Example 2: List the name, bridge number and location of all bridges using deck waterproofing membrane type B on roads subject to winter maintenance with rock salt de-icer.

Example 3: List the name, bridge number, location, inspection history and maintenance history of all bridges in region C that are classified as ancient monuments.

Example 4: List the name, bridge number and location of any bridge on the route M1 that has a weight restriction imposed.

The first part of each example indicates the information from the inventory that is required and the second part specifies the criteria that should be applied to ensure that the data reported only relates to bridges satisfying the criteria.

The first example is one that would be used regularly to check that the principal inspections of bridges are not being overlooked by mistake, an event that is quite possible on a few bridges when the stock contains, typically several thousand bridges.

Example 2 may arise if problems have been identified with a particular type of deck waterproofing membrane and it is required to identify the other bridges with this type of membrane especially if de-icers are used since these may penetrate into the deck and cause latent corrosion of the reinforcement.

The third example may arise if the heritage authority requests information on the condition and maintenance of bridges classified as ancient monuments.

The fourth example may arise during investigations into the effect of a load restriction on one bridge on traffic movements on its route.

These queries usually only take a few minutes to compose and can be saved for future use if necessary. The reports can be viewed on screen, printed or saved to file for electronic transmission.

This function of a BMS is very flexible and has numerous applications associated with day to day management activities.

3.3 CONDITION APPRAISAL

Bridges are usually designed and constructed to achieve a life of about 100 years hence it is important to monitor their condition periodically throughout their life in order to ensure that:

- they remain fit for purpose
- the level of deterioration is consistent with achieving the design life
- there are no obvious defects that affect the safety of the public.

These checks are the purpose of bridge inspection and the results can be used to provide information on the condition of a bridge. The term condition is quite general and means different things to different people. Guidelines for condition assessment based on a review of methods used in Europe and the United States are described in Deliverable D2. In general it is based on the results of superficial, general and major bridge inspections. A fourth type of inspection, an in-depth inspection, is sometimes carried out on bridges that have to be repaired and comprises extensive measurements on site and investigations in the laboratory.

The review found that there are two concepts of condition assessment of the whole structure. The first is based on a cumulative condition rating obtained from a weighted sum of the condition states of each element of the bridge. The second is based on a condition rating class where the condition of the bridge is considered to be equivalent to the condition state of the element in the poorest condition. The first concept enables bridges to be ranked in terms of condition.

More advanced methods of condition assessment are also reviewed in Deliverable D2. These include artificial intelligence methods such as neural networks, fuzzy logic and genetic algorithms and an example is given of the use of neural network model to categorise condition state of bridges suffering from reinforcement corrosion. It was found that the prediction of future condition remains a challenge, even when these advanced methods are employed. Further research is therefore needed on deterioration models and on the development of a database in order to be able to predict the future condition of bridges.

In order to use condition to monitor the deterioration of a bridge throughout its life it is necessary to make the definition more restrictive and precise and in particular it should be quantified. The work described in Deliverable D2 identified two main approaches for quantifying condition:

a) To make visual observations and simple tests to subjectively assess the condition on an arbitrary scale ranging, for example, from 1 (good condition) to 5 (very poor condition).

b) To measure physical/chemical parameters such as concrete strength, thickness of steel section, concrete resistivity and chloride content using more sophisticated tests.

Both approaches have significant disadvantages. The chief disadvantage of physical/ chemical measurements is that each measurement technique only takes account of one mode of deterioration and each element of the bridge may experience different deterioration mechanisms at different stages of their life.

The main causes of deterioration of construction materials and components are corrosion, freeze-thaw effects, alkali silica reaction and sulphate attack (Deliverable D11). Each cause will require different tests to establish its presence, find the extent of the deterioration, determine its rate of development and assess the consequences. Consideration of corrosion of reinforcing steel in concrete demonstrates the difficulties. The following sequence of tests would be needed to monitor the condition throughout the life of the bridge:

a) determine the cause of corrosion (chloride or carbonation) using sampling methods
b) having diagnosed the cause of corrosion determine the extent of the problem over the surface of the structure by more extensive sampling to ensure statistical significance; for example measure the area and location of de-bonded concrete (spalled, cracked, delaminated) in regions of general corrosion
c) establish the consequences of chloride contamination or carbonation by measuring the depth of cover, depth of carbonation, chloride depth profile, the threshold

chloride concentration for corrosion, and the time since corrosion initiation or the time to corrosion initiation
d) find where the reinforcement is already corroding by half cell potential measurements
e) establish the type of corrosion (localised or general) that is taking place by measuring the electrical potential gradient
f) measure the corrosion current density to estimate the rate of corrosion
g) expose the reinforcement to measure the remaining cross section of the steel bars in regions of localised corrosion

If these measurements were repeated periodically throughout the life of a bridge suffering from reinforcement corrosion the condition would be thoroughly monitored although it would still be difficult to express the condition in a concise quantitative form. The condition would be best represented by a multi-dimensional vector of the individual test results. In order to achieve satisfactory coverage of the bridge it would be necessary to carry out the measurement set at several locations. The high variance of results for several of the measurement techniques means that uncertainties would exist about how well the sample of measurement locations represents the condition of an element or the bridge. Real variations in the value of these measurements at different locations in the bridge lead to further confusion about the meaning of condition. Where measurements differ at different locations, suggesting variations in condition, it is debatable how the condition should be represented. Possibilities are:

(i) to take the average, medium or mode of the measurements at different points on an element
(ii) to take the worst case to represent the condition of the element.

The first case is appropriate if an overall assessment of the condition of the element is required or if the variance is small. More often, however, the earliest occurrence of defects at some point on an element is required and in this situation the worst case approach is more appropriate. This draws attention to a fundamental point - why do we need to know the condition? It would evidently be interesting to know the average condition of a bridge especially for network management purposes. However average values are misleading at the project level because it is possible for part of an element to have some measurements indicating the presence of defects where the average of the measurements indicates no defects. This is especially likely due to the high variance of some types of measurement. The element may therefore require maintenance work even though the average condition appears to indicate no defects.

Even for network level management the worst case approach is more likely to give a better representation of condition since it reflects the need for maintenance more reliably. The above discussion about the interpretation of the condition of a bridge suggests that the need for different levels of maintenance may provide a simple and relevant measure of condition.

The cost of physical/ chemical testing as a general method for determining condition could easily exceed the cost of maintenance and hence this approach is only likely to be used in exceptional circumstances. Traffic management could be required in order to carry out these tests on some bridge elements and the associated traffic disruption would further count against the physical/ chemical test approach to assessing condition. Returning to the discussion relating to the question ‘why do we want to know the condition of a bridge or its elements?’ there are a few additional answers:

- to provide the opportunity to carry out simpler, cheaper and less disruptive maintenance procedures before further deterioration necessitates more complex, expensive and disruptive work.
- To provide a global view of the condition of the stock of bridges.
- To provide feedback to designers and builders about durability of construction materials and components so that work on improvements can be effectively targeted.

These potential benefits of assessing bridge condition must be compared with the costs of undertaking the testing work. It appears that in most circumstances the benefit: cost ratio will not be high enough to support the testing approach. Testing would however be necessary prior to maintenance work to establish the best method and the extent of the work required to achieve a durable repair. The amount of testing needed prior to maintenance would be much reduced if the testing approach had been adopted for assessing condition and this would clearly count in favour of this approach. The results from testing are also often required in order to carry out the assessment of load carrying capacity of deteriorated structures.

An important advantage of the testing approach is that it increases knowledge of deterioration mechanisms that will provide feedback to designers and managers to help them improve durability and lower deterioration rates.

Another way of limiting the amount of the testing work needed which is described in Deliverable D2 is to use neural networks to try and derive a relationship between the test results and visual observations made by an inspector. After the neural network has been trained by supplying data on both visual observation and test results, it should be possible to just carry out the visual observation and to have this data improved by the neural network relationship. This should provide a more reliable condition assessment than that achieved with visual observations alone.

The main disadvantages of the subjective assessment of condition based on visual observations are:

- the subjectivity of the assessment can make the results vulnerable to bias
- visual observations cannot detect latent defects or the early stages of deterioration.

The first disadvantage can be largely overcome by developing a set of definitions for each condition state that are clearly discrete in the sense that there are distinct differences between the definitions for adjacent condition states. Discreteness limits the number of states that can be used to four or five in most cases. The effectiveness of a set of condition state definitions can be tested by arranging for a number of bridge inspectors to independently assess the condition state of a group of bridges in a statistically designed trial. A considerable amount of thought and iteration may be required to establish a satisfactory set of definitions and a number of sets may be needed to embrace different construction materials such as steel and concrete, and different forms of deterioration such as corrosion of steel and sulphate attack of concrete. The small number of states in a condition state system means that each state is associated with a maintenance strategy such as do nothing, preventative maintenance, minor repair work, major repair work, strengthening or replacement. This link between the condition state and maintenance strategy supplies a unifying theme for the BMS.

Condition state systems based on visual observations usually take account of both the severity and extent of deterioration. The severity of a defect is, however, usually of more significance than the extent in terms of maintenance needs. The extent of deterioration has more significance than severity in terms of the quantity and cost of maintenance work. Therefore in terms of the condition assessment the severity of deterioration is more significant whereas in terms of optimising maintenance costs the extent of deterioration is more significant. The limitation of condition assessment to visual observations of the severity and extent of deterioration usually means that is difficult to establish more than about three discrete condition states and this is barely adequate.

The second disadvantage relating to the limitations of visual observations for assessing condition is more important. Some defects that occur on bridges provide no visual indications and are classed as latent defects. Some latent defects ultimately produce secondary effects with observable indications when the primary latent defect becomes severe, but this usually occurs too late to prevent the necessity for major strengthening and refurbishment. Most defects only become visible when they have developed significantly. This means that more complex, costly, disruptive and extensive maintenance is needed than would have been the case if the deterioration had been detected sooner. In these circumstances the preventative maintenance strategy becomes, in effect, a disallowed option although systematic investigations are recommended to confirm the presence of latent defects. Preventative maintenance is often applied initially as part of the construction process but it generally has a limited life, which is short compared with the design life, and needs to be reapplied regularly if the protection is to be maintained. If the early stages of deterioration and breakdown of the protection provided by preventative maintenance are not detected, due to the limitations of visual inspection, then the time window for the effective reapplication will be missed, with the consequences described above.

The main advantage of the visual observation approach to assessing the condition of a bridge is operational. It can be carried as part of a bridge inspection without the requirement for additional access and traffic management and hence with little additional cost or disruption to traffic. The other main advantages are its simplicity and links with maintenance strategies.

The disadvantages associated with the two approaches to assessing condition discussed above suggest an approach comprising the best features of both. An approach based on the assessment of condition state by bridge inspectors can be recommended, but with the incorporation of sufficient non-destructive testing to enable latent defects to be detected and diagnosed in most circumstances. This approach will also permit more discrete condition states to be defined. It will not however evaluate the extent of deterioration of the area requiring maintenance. Further tests would be required if repair work becomes necessary although the preferred maintenance philosophy is to maintain the effectiveness of preventative measures applied during bridge construction so that the concrete remains undamaged.

Preventative maintenance is generally applied to entire elements so there is no need for tests to determine the area requiring maintenance. An example of a condition state system for concrete bridges vulnerable to reinforcement corrosion is provided in Table 4.

The assessment of condition is usually carried out for each element of a bridge. This gives rise to questions about if and how the condition assessments should be combined to give an overall condition for the bridge. For project level management of a particular bridge it is probably best not to combine the condition assessments for each element since these relate most closely to the maintenance requirements. For network level management where the overall condition of a stock of bridges may be wanted, some type of aggregation of condition states must take place. Possible methods of aggregation are:

- the mean value of the condition states for all the elements of a bridge
- the median value of the condition states for all the elements of a bridge
- the mode value of the condition states for all the elements of a bridge
- a frequency distribution of condition states of the different elements comprising the bridge
- a weighted mean value
- worst case value.

The assessment of condition is primarily associated with the inspection module of the BMS. There are four levels of inspection that are generally adopted – superficial, general, principal and special. Superficial inspections take place annually and consist of a brief visual examination to elicit any serious defects, but no condition assessment is made. This type of inspection is often combined with the annual visit for basic routine maintenance to carry out activities such as cleaning drains and controlling the growth of vegetation. The results of superficial inspections are not usually recorded in the BMS. General inspections are carried out about every 2 years and consist of visual observations made without special access arrangements. An assessment of condition is made of those elements that can be observed, but some elements will be obstructed from view and hence cannot be inspected. A condition assessment will not be possible in these elements. Principal inspections are carried out about every six years and involve detailed visual observations supplemented by some non-destructive testing and sampling. Provision is made to enable the inspector to gain close access to all parts of the bridge and a condition assessment is made for each element of the bridge. Special inspections are carried out as required and not at a regular frequency. They are used to establish the cause and extent of the deterioration and are usually carried out prior to repair work so that it can be correctly specified. Special inspections involve the extensive application of non-destructive testing and material sampling. Condition assessments made during general and principal inspections are normally stored in the BMS. The results of special inspections are not always stored in the BMS. It is however recommended that test results are stored in the BMS since this will help when assessing the rate of deterioration.

Table 4
Condition state system for concrete bridges vulnerable to reinforcement corrosion

Condition State	Non Destructive Tests Used	Criteria	Maintenance Strategy
1.	Cover depth Carbonation depth Chloride depth profile Half Cell potential	No visible defects Cover depth > 30 mm Carbonation depth < 10 mm Chloride penetration depth < 10 mm Half Cell potentials in passive zone	DO NOTHING
2.	Cover depth Carbonation depth Chloride depth profile Half Cell potential	No visible defects Ratio of cover depth : carbonation depth < 1.5 Ratio of cover depth : chloride penetration depth < 1.5 Half Cell potentials in passive zone	Preventative Maintenance to retard carbonation and chloride ingress
3.	Half Cell potential	No visible defects Half Cell potentials in the active zone	Preventative maintenance to reduce the corrosion rate
4.	Half Cell potential Corrosion Current	Visible indications of corrosion Half Cell potentials in active zone Potential gradient low Corrosion current moderate or high	Repair concrete + Preventative maintenance to reduce the corrosion rate
5.	Half Cell potential Resistivity Chloride depth profile	Half Cell potentials in the active zone Potential gradient high Resistivity low Chloride penetration depth > cover depth	Repair damaged concrete + Preventative maintenance to reduce the corrosion rate and prevent the development of incipient anodes
6.	Remaining cross section of reinforcement by invasive examination Area of de-bonded concrete by observations and delamination soundings.	Remaining cross section < 90% Area de-bonded > 10%	Carry out an assessment of load carrying capacity and strengthen if necessary

The main purpose of bridge inspections can be summarised as:

- to decide if a more detailed inspection is needed
- to assess maintenance needs and strategy
- to assess the safety of users and to decide if a structural assessment is needed
- to reduce the risk of unexpected failure
- to comply with regulations
- to assess the condition of a bridge element.

Information about condition is stored in the inventory database and can be combined with other data in the inventory. For example the frequency distributions of the condition of different elements of a bridge can be aggregated to include only bridges

- in a given region or
- in a given age range or
- on a particular route or
- in a particular type of environment or
- within a given range of span length.

Alternatively the condition of elements that satisfy various limitations can be aggregated. Examples include:

- bridge decks with a particular type of waterproofing membrane
- bridge decks with a particular type of expansion joint
- bridge piers on roads treated with de-icing salt.

The above examples of criteria defining the selection of bridges or elements from the entire stock are very simple and it is possible to combine simple criteria to form a complex criterion using logical operators such as AND, OR, and NOT.

The discussion of condition assessment has been detailed because the information is of crucial importance and is used for all the other modules of the BMS, ie

- assessment of load carrying capacity
- rate of deterioration
- optimisation of maintenance costs
- deciding the maintenance strategy
- prioritising maintenance work.

3.4 ASSESSMENT OF LOAD CARRYING CAPACITY

The previous section discussed the assessment of condition which is one factor that decides whether or not maintenance is necessary. Maintenance needs, based on condition assessment are usually decided by considering the lifetime economics of the bridge. In other words maintenance is carried out if it leads to a reduction in whole life cost. Maintenance work can also be sanctioned for aesthetic, political, social or environmental reasons, but these are too unpredictable to be included in the BMS at present and hence must be left to the judgement of local engineers. Another factor that plays an important role in deciding on maintenance needs is the load carrying capacity and whether it is sufficient to sustain the applied loads. The maintenance needs arising from an inadequate load carrying capacity are essential in nature. In other words if the load carrying capacity is inadequate, load restrictions must be imposed until the bridge is strengthened to maintain safety. The only exception to this rule occurs when there is compelling evidence that any failure would be gradual such that inspection and monitoring would permit loads to be reduced prior to an anticipated failure. Thus maintenance required because of inadequate load carrying capacity is more important than that needed because of poor condition and normally has a higher priority as a result. There is, however, a strong interaction between condition and load carrying capacity since deterioration of condition almost invariably reduces the load carrying capacity. In the last section it was seen that when the condition becomes sufficiently poor the recommendation was to carry out a structural assessment to check the capacity. The situation regarding the link between condition and load carrying capacity is less straight forward than it appears. The significant parameter is actually the difference between the actual capacity of a bridge at a given time and the required capacity based on the possible loads carried at that time; the condition only affects the actual capacity. Some bridges have considerable reserves of strength and can undergo substantial deterioration before their capacity becomes substandard. In these cases the need for maintenance is more likely to depend on the condition rather than the load carrying capacity. For example spalling concrete may become a hazard for users or the poor aesthetics of a deteriorated bridge may lead to a loss of public confidence before the capacity becomes inadequate. In other cases the difference between the actual and required load carrying capacity may be quite small and relatively small amounts of deterioration could make the bridge substandard. There are less reserves of strength in some parts of a bridge than in others and it is important to know the location of these structurally critical areas, because more attention should be given to condition assessment in these locations (Deliverable D1).

The above discussion explains the necessity for structural assessments to establish a measure of load carrying capacity and the location of structurally critical areas on a bridge. Recommendations for methods of assessment of load carrying capacity are described in Deliverable D10. These methods are based on a review of current assessment procedures used in the countries participating in BRIME, including details of the characteristics of existing structures, the standards used in design and assessment, and the experimental assessment methods. The aim is to show how suitable and realistic assumptions for material, and structural properties and traffic loads can be obtained and implemented in a structural assessment.

To assess adequately the resistance properties of structural elements, data and models of loads and material strength need to be gathered. With regard to loading, the work described in Deliverable D5 covers traffic loads, and increases in traffic loading are taken into account by the application of extreme traffic situations and the definition of a sufficient safety level. With regard to material strength, summaries of time-independent statistical properties are referenced for reinforced and prestressed concrete, steel, masonry and timber structures.

Bridge assessment in the partner countries generally is based on classical structural calculations in which the load effects are determined by structural analysis. The rules used are provided mainly by design standards with additional rules relating to testing methods, including load testing. Bridge assessment is usually based on either a deterministic or a semi-probabilistic approach; partial safety factors are used in the semi-probabilistic approach. These methods are sometimes considered to be conservative. A new approach taking into account the uncertainties of variables is emerging and reliability calculations are beginning to be introduced. The target reliability index is becoming the governing factor for assessment.

Deliverable D10 recommends an assessment methodology based on five assessment levels going from a method using simple analysis and codified requirements (level 1) to a sophisticated assessment using a full probabilistic reliability analysis (level 5).

The review of current practice for assessing load carrying capacity was the starting point for the modelling of deteriorated structures that is described in Deliverable D11.

The assessment of bridge strength is also an important input for the cost evaluation of various maintenance strategies and the decision making process (Deliverable D7) and for the priority ranking (Deliverable D12). A knowledge of bridge strength is essential for the routing of exceptional load vehicles and for the safe management of traffic.

A pass/fail outcome to a structural assessment is only barely sufficient because its use is limited to a particular point in time and it provides only a crude assessment of the age at which a bridge may become substandard. An estimate of the date for the next assessment of capacity cannot therefore be made.

The evaluation of the variation of load carrying capacity with time remains a challenge and requires further investigation. Methods for quantifying the structural effects of material deterioration so that they can be incorporated into the assessment of the load carrying capacity of bridges are described in Deliverable D11. The methodology followed is divided into 3 stages.

i) identification and diagnosis of the common forms of deterioration present in the European bridge stock. From this survey, it is apparent that corrosion of steel due to carbonation and chloride contamination is the most common problem, and that ASR, sulphate attack and freeze-thaw action also occur at a significant frequency.

ii) evaluation of the existing methods for incorporating deterioration in assessment e.g. reduced cross-sectional area, modified stress-strain relationship and modified bond properties.

iii) investigation of straight-forward methods of taking account of deterioration in the determination of structural strength of components. This is carried out for deterioration caused by corrosion, ASR and freeze-thaw action.

Models to predict deterioration are often based on experiments using laboratory specimens, and need to be calibrated by comparison with site measurements and non-destructive tests. Only those site measurements that can be carried out reasonably quickly and minimise the disruption to site operations can be realistically used for predicting deterioration. Deterioration processes do not develop at a linear rate due to specific conditions on site and this complicates the methods used for making predictions.

For bridge management purposes structural assessments are required in order to:

- determine the reserves of strength of different parts of a bridge at different ages and conditions
- estimate the date for the next structural assessment
- estimate the date at which any part of a bridge will become substandard.

These estimates will be derived from a knowledge of the rate of deterioration and the reserves of strength measured at the last structural assessment. The reserves of strength will also depend on changes in loading although these are not predictable. Changes in loading will therefore generate a need for an assessment when they take place. At present the algorithms linking strength and rate of deterioration are very approximate with the result that the estimated dates above will be conservative. An improved understanding of the strength of deteriorated bridges and the factors affecting the rate of deterioration should lead to improved algorithms and estimates. This should permit bridges to be strengthened or replaced before they become substandard thereby avoiding loading restrictions and the disruption that usually results. Improved algorithms should also enable a reasonable estimate of remaining life up to assessment failure to be obtained. The aggregation of residual lives for the bridges in a stock would enable the BMS to determine the number and location of bridges requiring strengthening or replacement each year and to adjust the level of preventative maintenance to reduce the rate of deterioration if necessary.

The major factor holding up the calculation of reasonable estimates of remaining life is establishing how deterioration influences the strength of a structure (Deliverable D11). Deterioration can result from environmental influences and from faults associated with design and construction. Usually deterioration results from a combination of different problems and this makes it a difficult process to model. For example reinforcement corrosion in bearing shelves and cross-heads usually results from the failure of an expansion joint which leaks, allowing saline water to fall onto the concrete element which has insufficient falls and drainage. The salt water then ponds allowing chloride ions to rapidly penetrate the concrete causing corrosion, especially if construction practices resulted in the formation of cracks in the concrete surface. Many physical processes are involved and it is easy to see the modelling difficulties. In a similar way the effect of a known level of deterioration on the strength of an element is difficult to estimate because it also depends on:

- the location of deterioration
- the number or area of defects
- the severity of defects.

and condition only really accounts for severity. The real problem is the non-uniformity of deterioration. For example if a reinforcing bar was uniformly corroded over its entire surface, a reasonable estimate of its strength could be obtained from the cross section of steel remaining. In practice, however, reinforcement corrosion is never uniform and is often in the form of pits which represent an extreme non-uniform situation. For steel corrosion the effect on strength may not be limited to reduced dimensions, but may also involve the ductility which is known to be reduced by corrosion and especially pitting corrosion. The situation is further complicated because the strength depends on a number of different load effects namely: flexure, shear, bond, bearing and deflection. To assess the strength of deteriorated concrete necessitates a knowledge of the tensile strength, bearing strength and elastic modulus as well as the compressive strength. The composite action between steel and concrete in reinforced concrete depends on the bond between these two materials and the mechanism by which corrosion affects the bond is not well understood. In undamaged concrete the bond depends on the bar type and compressive strength of the concrete but it is not known how levels of corrosion insufficient to fracture the concrete affect the bond. When corrosion causes the concrete to fracture leading to spalls, cracks and delamination it is clear that the bond is significantly reduced, but the extent is not known. These uncertainties and shortcomings to knowledge mean that any attempt to relate deterioration and strength is based largely on the engineering judgement of experts and is inevitably likely to be very conservative. The current practice of measuring the compressive strength of concrete and the tensile strength of steel to take account of deterioration in structural assessments is necessary but not sufficient. More extensive testing is, however, not justified until there is a better understanding of how the non uniform variation of physical properties of steel and concrete affect the strength of these materials; this can only be achieved by fundamental research.

At the present time, the only effective ways in which a BMS can use information from structural assessments is to:

- determine the reserves of strength assuming no deterioration
- locate the critical structural areas on a bridge
- assess the condition particularly in the critical areas
- use engineering judgement to take account of strength and deterioration, and decide whether strengthening is needed.

Another problem is to evaluate the effect of strength deficiencies in one element on the strength of the whole bridge. The stresses in one element are often redistributed into other elements so that the strength of the bridge is greater than would be expected from the strength of the individual elements. The combination of all these uncertainties means that in order to maintain the risk of failure at an acceptable level the assessment of the effect of deterioration on strength will have to be conservative. Bridges with low reserves of strength will probably need to be strengthened if they suffer any significant deterioration in critical areas.

The prediction of the load carrying capacity in the future and the relationship between strength and condition remain some way from being achieved.

3.5 RATE OF DETERIORATION

It is important to know the rate of deterioration of bridge elements because it allows future maintenance to be planned. This enables the bridge manager to assess the best time to carry out maintenance work. There are significant costs involved in carrying out maintenance work too soon or too late. The cost of maintenance is sensitive to the time when it is carried out for two reasons:

(i) in the calculation of whole life cost the cost of maintenance work shows a reduction by a factor of $(1.06)^{-n}$, where the discount rate is 6% and n is the age of the bridge when maintenance is carried out, to give the net present value (NPV).

(ii) maintenance costs change disproportionately for each unit increase in condition state as the complexity of maintenance operations increase; the level of disruption to users resulting from the maintenance work often mirrors the increased cost.

It appears that the best time to carry out maintenance is just before a transition occurs between one condition state and the next poorer condition state. This is because a large step increase in cost occurs at the time of transition whereas costs increase only slowly during the interval spent within a particular condition state. The current knowledge of how condition varies with time is not sufficient to estimate this ideal time for maintenance more than approximately, but it seems like a worthwhile venture nevertheless. It can be seen that the consequences of carrying out maintenance too late are more serious than doing the work too soon so it is best to err toward early maintenance. There have, however, been cases where the assessment of condition has been incorrect and maintenance work appropriate for a higher condition state has been carried out unnecessarily and wastefully. This emphasises that it is essential to carry out the condition assessment properly and demonstrates the serious waste of money that can occur if maintenance work is carried out much too soon.

The situation regarding disruption to users as a result of maintenance work is also influenced to some extent by whether the work is carried out too soon or too late. When account is taken of the growth of traffic each year there may be less disruption if maintenance is carried out too soon, but if early maintenance has the result of requiring an extra maintenance treatment during the life of the bridge then the whole life disruption will probably be increased. Carrying out maintenance too late will usually result in more disruption because the more complex maintenance treatment required will generally result in more extensive traffic management over a longer time period. Traffic management and delay costs increase when maintenance work is deferred as shown in Figure 1 because further deterioration increases the duration of repairs and traffic growth leads to higher traffic flows.

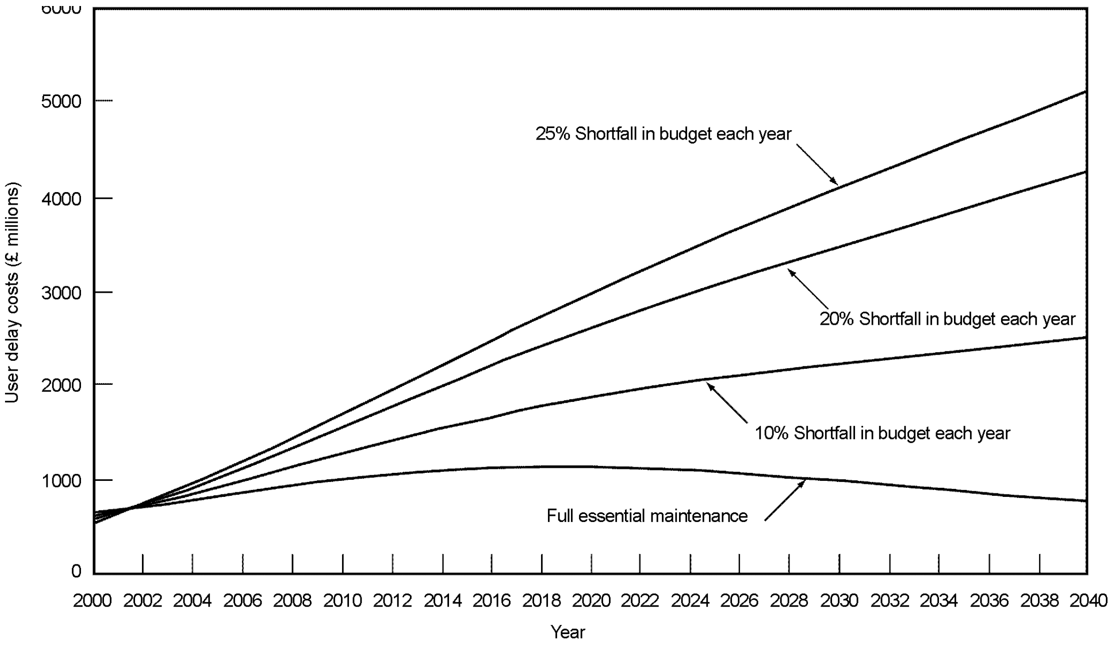


Figure 1: Traffic delay costs due to underfunding

A knowledge of the rate of deterioration also enables the bridge manager to

- estimate the residual life or time till the poorest condition state is reached
- decide on a suitable maintenance strategy for a bridge at different ages
- prioritise maintenance (rapidly deteriorating bridges have a higher priority because there is more chance maintaining too late)
- calculate a budget for bridge maintenance from information about how many bridges need maintenance each year.

One of the most important applications of deterioration rates is to determine the cost and disruption consequences of deferring maintenance work and less frequently of advancing maintenance work. It is often necessary for maintenance to be carried out at a non-optimal time for operational reasons such as:

- budget limitations that mean some work has to be deferred
- to complete maintenance work on a bridge and avoid a return for a long period, the work on some bridges may need to be advanced or delayed
- to allow bridges on the same road to be maintained simultaneously to limit traffic disruption.

Deterioration is a natural process that should be expected to occur since it is unrealistic to expect a bridge or any other structure to remain serviceable forever. The bridge manager's objective is to control the rate of deterioration so that the required serviceable life of the bridge is achieved. This objective can be satisfied by an appropriate design using durable materials or by applying maintenance at appropriate ages during the life of the bridge. In practice a combination of these two approaches is adopted in most cases.

The condition of a stock of bridges usually decreases as the average age of the stock increases. When the number of new bridges built during a period of time significantly exceeds the number demolished the average condition of the bridge stock tends to improve. If the average condition of a bridge stock is shown to be deteriorating too quickly it will be necessary to undertake a special programme of maintenance and replacements to retard the rate of deterioration and improve the average condition of the stock. The average condition and its rate of change give only an approximate measure of the rate of deterioration and its consequences. A better approach is to use the area enclosed by a graph of average condition versus age for the bridge stock as a measure of stock condition and the rate of change of this area as the rate of deterioration (Figure 2). This approach also indicates the rate of deterioration for bridges in particular age ranges and can therefore help in targeting maintenance work. Another useful procedure is to measure the rate of deterioration of groups of bridges that were in particular condition states a set period ago, say five years. This will indicate if the rate of deterioration is unusually high for groups of bridges in a particular condition state. The age and condition of bridges are the two factors that most influence the rate of deterioration of the bridge stock.

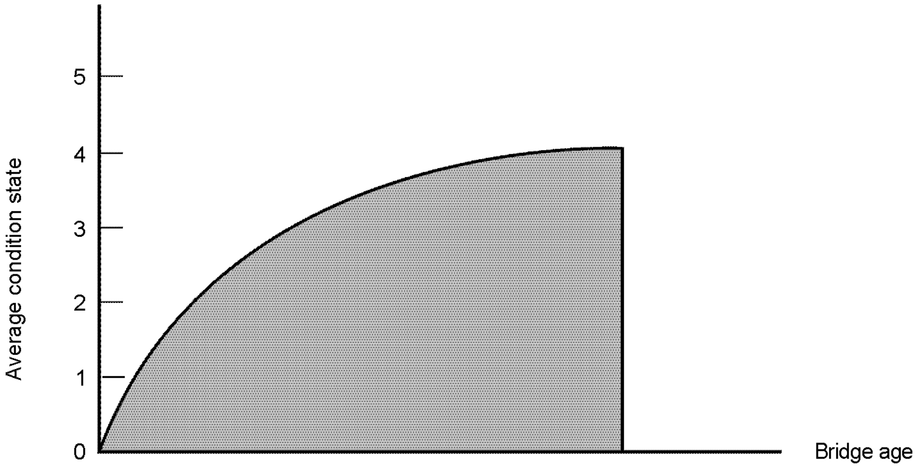


Figure 2: Condition of bridge stock represented by area under graph of average condition state vs. bridge age

The level of maintenance is the other factor that influences the rate of deterioration of the bridge stock although the effect it has on the rate of deterioration of particular bridges is even more marked. The condition of a bridge usually decreases until some maintenance work is carried out. Maintenance can have two effects:

- slowing the rate of deterioration
- improving condition.

Preventative maintenance has the first effect whereas repair work or rehabilitation should have both effects. A graph of condition state versus age for a bridge therefore consists of a number of discontinuous sections often leading to a saw tooth shape. The discontinuities occur at the ages when maintenance is carried out and result in a change of numeric value of gradient for preventative maintenance and a change in both sign and value of the gradient for repair/rehabilitation work. It should be noted that normally repair/rehabilitation work produces only a partial improvement in condition so that the condition when initially built is not recovered. Strengthening work on the other hand can raise the load carrying capacity to a value greater than that when built. In terms of its effect on the load carrying capacity of a bridge deterioration is most significant when it takes place in structurally critical parts of the bridge. However, it is unlikely, given the current state of knowledge, that it will be possible to estimate the rate of reduction in load carrying capacity from the rate of deterioration in the near future. The rate of deterioration may nevertheless be used to indicate when it is necessary to carry out a structural assessment.

To use information about the rate of deterioration to predict the condition state at a future age a procedure must be found to take account of the effect of maintenance work. One procedure is based on two factors:

- the immediate improvement in condition resulting from the maintenance work
- the change in gradient of the condition – time graph following the maintenance work.

Types of bridge or element with a high rate of deterioration can be identified and provide an indication as to whether the cause is poor design/materials or insufficient maintenance. This feedback can then be used to eliminate problems in the future.

Deterioration of bridges has a number of possible effects:

- reduces the strength
- makes it unsafe for users, for example due to falling masonry
- reduces the life
- impairs the appearance

It is the extent of these effects at different ages which largely determines the type of maintenance required. Although deterioration reduces strength this may not be significant; it will depend on the location of deterioration and the reserves of strength. A defect may or may not affect the safety of users. For example spalling concrete from the soffit of a bridge over a small river may have little effect on the safety of users whereas a similar defect in a bridge spanning a busy road or railway could have a serious effect on users. Deterioration generally results in a reduction in life although the magnitude will vary and will not always be significant. The appearance of a bridge is often impaired by deterioration and this can sometimes lead to a loss of public confidence in the structure.

It is difficult to generalise about the rate at which bridge elements deteriorate because different bridges and even different parts of bridges are exposed to different macro- and micro-climates. Even bridge elements of nominally similar construction and materials can have variations in concrete mix, cover depth and latent defects which can significantly influence the type of pathology and the deterioration rate. The two main approaches to determining rate of deterioration, physical and stochastic modelling are described in Deliverable D8.

The approach described in detail in Deliverable D8 is physical modelling applied to a particular deterioration process namely the ingress of chloride ions into concrete bridge elements. This has a limited goal in terms of the bridge management system as it deals with only a single deterioration mechanism; it is limited to the initiation phase of the corrosion process although it also deals with monitoring corrosion within a bridge and it proposes a durability surveillance system. It does however illustrate the difficulties in attempting to predict the rate of future deterioration.

The chloride ingress model has at present serious limitations as far as BMS is concerned. The model can predict when there will be a risk of corrosion initiation, but it cannot predict the corrosion rate of reinforcement. It can be useful for forecasting possible maintenance actions, but not for assessing deterioration and structural capacity.

Further research is therefore necessary to improve knowledge of chloride ion penetration models through the constitution of a database collecting measurements on site and in the laboratory, and most importantly to develop models for the propagation phase of corrosion.

3.6 DECIDING MAINTENANCE REQUIREMENTS

The primary decisions associated with the maintenance requirements for a bridge are:

- the maintenance strategy
- the maintenance method
- the extent of maintenance
- the age when maintenance is carried out.

The maintenance strategy for the network is often a policy decision. It is particularly important to select the appropriate strategy to minimise costs and maximise the effectiveness of maintenance. The options for maintenance strategy include:

(a) do nothing until a bridge becomes unsafe or substandard, when some form of strengthening or traffic restriction will be needed
(b) do nothing until the condition deteriorates to a benchmark value, when repair work will be needed to improve the condition
(c) carry out regular preventative maintenance to reduce the rate of deterioration thereby avoiding or delaying the need for repair work, strengthening or traffic restrictions.

Replacement of bridges when they become unsafe or substandard is an alternative to strengthening and the decision between the two strategies is usually based on economics.

The main advantages of strategy (a) are:

- no maintenance is necessary until a bridge becomes unsafe or substandard thereby deferring expenditure and traffic disruption to later in the life of the bridge
- the avoidance of maintenance costs and traffic disruption on bridges that do not become unsafe or substandard during their required life.

Both of these advantages will help to reduce the whole life cost.

The main disadvantages of strategy (a) are:

- the cost of strengthening work and the associated traffic disruption are high leading to increases in the whole life cost
- it is possible that large numbers of bridges may need strengthening at certain times reflecting the non uniform rate of bridge construction in the past. Industry has difficulty reacting to markedly non-uniform maintenance requirements leading to delays in carrying out the work and a significant number of bridges with traffic restrictions, resulting in serious disruption to the movement of vehicles.
- defects may arise due to deterioration which although not affecting safety may increase the rate of deterioration and seriously detract from the appearance of the bridge. This can result in the need for strengthening at a lower age and a loss in public confidence about the safety of the bridge.

This strategy may be suitable for a very small number of bridges on which the optimal decision is to replace them and to let them last as long as possible.

The main advantages of strategy (b) are:

- no maintenance is needed until a bridge reaches the benchmark condition value thereby deferring expenditure and traffic disruption to later in the life of the bridge
- to retard the rate of deterioration thereby reducing the chance that strengthening work will be needed
- the avoidance of maintenance work and its associated costs and traffic disruption on some bridges where the rate of deterioration is low with the result that the benchmark condition value is not reached during the lifetime of the bridge.

These three advantages should help to reduce lifetime costs and traffic disruption.

The main disadvantages of strategy (b) are:

- The cost of repair work and the associated traffic disruption can be substantial.
- In years when large numbers of bridges need repair work the industry may not be able to react quickly enough leading to delays in carrying out the work. The increased rate of deterioration on these bridges will advance the time when strengthening is needed.
- If the benchmark condition triggering repair work is set at too poor a condition, the rate of deterioration can be increased and the visual appearance can be significantly affected before the benchmark value is reached.

The main advantages of strategy (c) are:

- Preventative maintenance is cheap in comparison with repairs and strengthening and can usually be carried out with little disruption to traffic.
- The rate of deterioration is retarded substantially, especially if the preventative maintenance is applied from new, and will delay or avoid the need for repairs and strengthening.

These two advantages will tend to reduce lifetime costs and traffic disruption.

The main disadvantages of strategy (c) are:

- More frequent maintenance is required; typically preventative maintenance requires re-application about every 20 years although further development work could result in longer intervals between preventative maintenance events.
- Preventative maintenance by its nature is applied to all the bridges in the stock before it is known whether or not it is necessary. Some bridges may deteriorate very slowly or have substantial reserves of strength and hence may not need repair or strengthening even without preventative maintenance. For these bridges preventative maintenance work would be wasteful, but our current state of knowledge is not sufficient to be able to identify them. It is therefore necessary to apply preventative maintenance to all bridges in the stock, although there may be scope for limiting the application to structurally critical zones and to areas vulnerable to deterioration such as areas exposed to salt spray or under leaking expansion joints.

These disadvantages will tend to increase lifetime costs.

The choice of strategy depends on many factors but the preventative maintenance strategy is usually preferred when:

- it can be applied from new
- a maintenance life of more than 20 years can be achieved
- the majority of the bridge stock is likely to require more than one session of repair work or strengthening work resulting from deterioration during its life.

In practice, in the past, the maintenance strategy has not been considered until defects were observed at which point preventative maintenance is no longer an appropriate maintenance strategy. The condition state of a bridge generally determines which maintenance strategies are possible.

The choice of maintenance method will be considered in some detail later in this deliverable although it is pertinent to say here that the number of maintenance options from which a decision has to be make are substantially reduced when the maintenance strategy is pre-determined.

The extent of maintenance work should be decided on the basis of achieving a durable result with a life of at least 40 years. Partial repair work can only be regarded as a short-term measure that is rarely justified on economic grounds. The correct extent of maintenance work is normally decided on the basis of a thorough survey and tests carried out on the bridge.

The time at which maintenance is carried out can have a significant bearing on the efficiency and effectiveness of the strategy. Two possible approaches to deciding the best time to carry out maintenance are:

a) to consider the best maintenance option at a particular time, for example when funds become available (Deliverable 7)
b) to consider the best maintenance option at regular intervals, say 5 years, in the future.

Approach (a) develops decision criteria that help to choose the best maintenance option for a given bridge at a particular time and is described in Deliverable D7. It is based on a global cost analysis that includes safety, durability, functionality and socio-economic factors, and considers all the costs involved in construction, inspection, maintenance, repair, failure, road usage, and replacement. The strategy consists of minimising the global cost while keeping the lifetime reliability of the bridge above a minimum allowable value.

Three difficulties are encountered with respect to the application of this methodology. The first concerns the constitution of a database containing costs, especially indirect costs and failure costs. The second is related to the necessity of predicting the future behaviour of bridges and the probability of failure for the various alternatives. It is clear that, as indicated in previous sections, additional research work is needed for predicting the future deterioration of both structural elements and non-structural components, when the option involves deferring maintenance work for a significant period of time. The third is the difficulty of determining the best time to carry out maintenance: it may, for example, be better to delay the proposed maintenance work if the rate of deterioration is sufficiently low to avoid a transition in condition state. In some cases, it could be preferable to permit deterioration to continue for some time, incurring a transition in condition state, and then to carry out more extensive maintenance. Early maintenance is not necessarily the best and to determine the optimum time the following factors need to be considered:

- the current condition
- the rate of deterioration
- the future life required
- the maintenance cost
- the discount rate for calculating whole life cost
- the type of road and the traffic management needed for the maintenance work
- the current traffic flow rate and rate of traffic growth.

The second approach (b) does take account of these factors and hence determines the optimum time for maintenance in order to minimise lifetime costs and traffic disruption. The disadvantage of this approach is the complexity of the algorithms needed, although with the power of modern computers this should not be overemphasised.

An optimisation process involves the minimisation or maximisation of an objective function. It may also involve a number of constraints. For optimising bridge maintenance a typical objective function is the whole life cost, which requires minimisation. The whole life cost should include engineering, traffic management and traffic delay costs because on busy roads the latter can be a major contribution to the overall cost. Possible optimisation constraints are:

(i) a benchmark value for probability of failure
(ii) a benchmark value for condition
(iii) no constraint.

The first constraint implies that bridges will be maintained in a safe condition throughout their life. The second constraint implies that the condition of the bridge will not be allowed to deteriorate beyond the benchmark value. The 'no constraint' option is the least restrictive. It does not imply that unsafe bridges can continue in service because this is not permitted. If a bridge became substandard the maintenance options would be between strengthening/replacement or traffic restriction, the decision being based on the relative increases in whole life costs associated with the two options. On a busy road the cost of strengthening/replacement is almost certain to be less than the costs associated with continuous traffic restrictions. On lightly trafficked roads the cost of traffic restrictions may be less than strengthening/replacement, although site specific factors are likely to play a significant part in assessing costs. The 'no constraint' option would result in traffic restrictions being imposed on some bridges, although the consequences of the restrictions would be small.

The first constraint would by comparison result in no long term traffic restrictions being imposed on any bridge. In practical terms it is usually difficult to use the first constraint because the probability of failure is not known unless detailed structural assessments are made at regular intervals. Furthermore it would be necessary to know how the probability of failure changes with increasing age. This will depend on the rate of deterioration in structurally critical areas. However such relationships are not properly understood and it is unrealistic to expect the probability of failure to be predicted with any degree of accuracy in the short term, except for some deterioration mechanisms such as fatigue of steel. Condition values are however often available from inspections allowing the second constraint to be adopted. This constraint provides some assurance that the condition of individual bridges and the bridge stock will not deteriorate too far. This assurance is achieved at some cost compared with the no constraint option because the imposition of constraints will lead to a higher value of the minimum whole life cost.

Maintenance work clearly has to take account of both the load carrying capacity and probability of failure and the condition. In view of the current limitations of knowledge a pragmatic approach would be:

(a) to predict how the condition will change with time in the structurally critical zones

(b) to recommend a structural assessment when the condition deteriorates to a state consistent with a reduction of strength

(c) to either strengthen/replace or impose traffic restrictions if the assessment criterion is failed

(d) to consider carrying out repairs if these will reduce the whole life cost and carry out a further structural assessment at a suitable interval if the assessment criterion is passed.

Thus the need for strengthening or replacement is linked indirectly to the condition via a structural assessment.

In most cases on major roads and sometimes on relatively minor roads the cost of bridge maintenance is dominated by the contribution of traffic management costs and traffic delay costs. Major savings can be made by maintaining traffic movements during maintenance work and by minimising the duration of restrictions even if this means providing temporary support to the bridge. There will of course be some parts of bridges on busy roads that can be maintained without implications for the traffic.

Decisions about maintenance options pertain to the circumstances associated with particular bridges such as the condition and extent of maintenance needed and hence are especially associated with project level bridge management. Decisions about the maintenance strategy can be policy led and are therefore more closely associated with network level bridge management. Network level management algorithms can be developed to predict the number of bridges requiring different degrees of maintenance each year but these algorithms cannot identify the particular bridges needing maintenance. This information can only be obtained from project level algorithms using bridge specific information. Network level information can be obtained by the aggregation of project level information and this can be employed to test the effectiveness of network level algorithms.

Ideally decisions about maintenance methods should involve aspects of safety, durability, functionality, economy, environment and sociology. Environmental and social factors are difficult to represent in monetary terms and have therefore not been considered by existing bridge management systems.

The followings costs should be evaluated when calculating the whole life cost of a bridge: design, construction, inspection, assessment, testing, preventative maintenance, repair, strengthening, replacement, demolition, traffic management, traffic delay and salvage value.

The ideal situation is for the spend on each of preventative maintenance, repairs and strengthening/replacement to be constant. This can only be achieved if there is sufficient money spent on preventative maintenance and repairs to control the deterioration rate at a reasonable level. If deterioration occurs too quickly the numbers of bridges requiring strengthening/replacement will increase to consume the entire maintenance budget resulting in further increases in deterioration rate and the number of substandard bridges (Figures 3a and 3b).

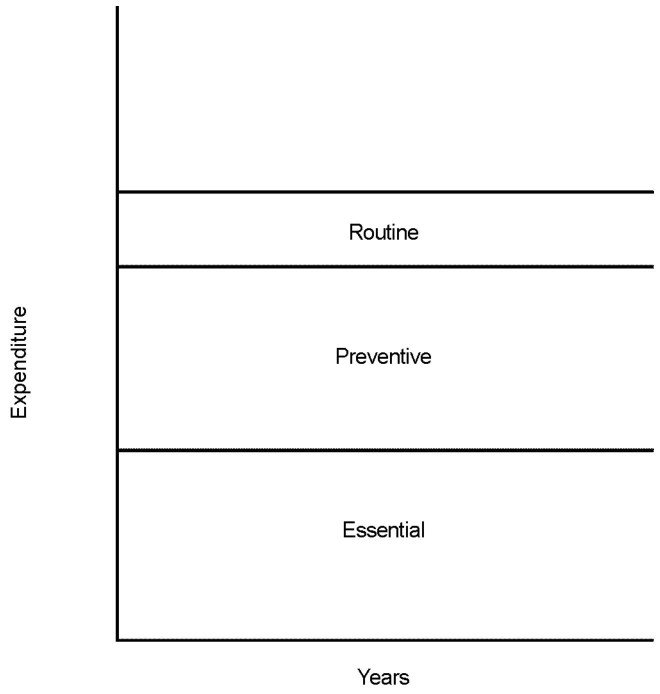


Figure 3a: Ideal bridge maintenance programme

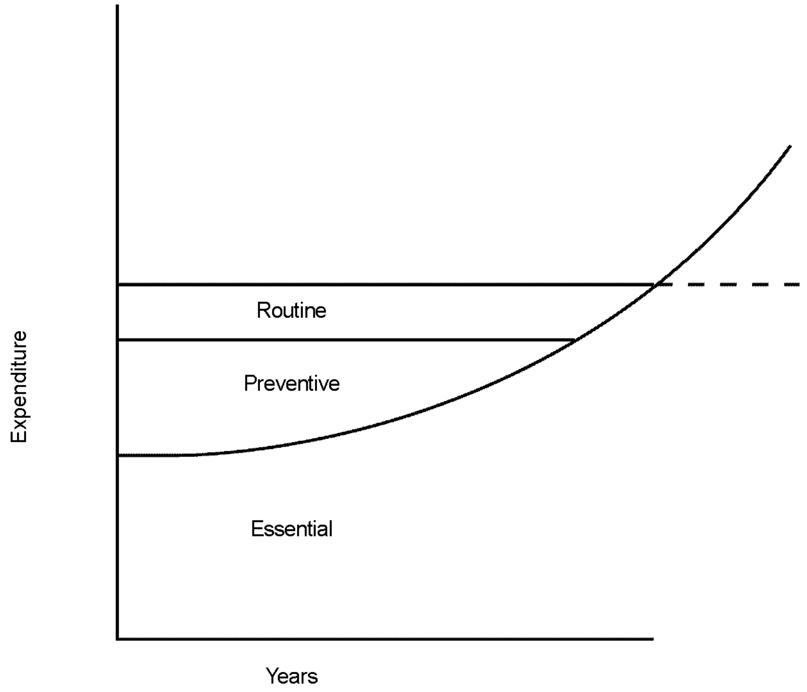


Figure 3b: Effect of long term underfunding

The optimisation process outputs an optimal maintenance programme that specifies what, if any, maintenance is needed on each element of every bridge in the stock each year in the future for the period of optimisation. The period of optimisation is not critical and can range from as little as 10 years to the bridge design life. All predictions are approximations and the further into the future that predictions are made the greater the errors. This is not however a major problem since maintenance planning is normally limited to about 10 years in the future where errors should be small. Regular updating of the data and regular re-application of the optimisation algorithm should ensure the reliability of predictions at least up to 10 years ahead. Optimisation algorithms can only take account of predictable processes such as natural deterioration. They cannot respond to events such as accidental damage, vandalism, natural disasters and political factors. Engineering judgement will still be necessary to deal with maintenance work arising from these events. Optimisation is primarily a project level management tool and while aggregation of the results for individual bridges provides a maintenance programme for the network that is optimal in some sense at the network level it cannot take account of the following actions that could reduce traffic management and delay costs:

- maintaining a group of adjacent bridges on a route in a single contract
- combining pavement and bridge maintenance
- combining several maintenance jobs on a bridge so that they can be done at the same time, involving the deferral of some work and the advancement of other work.

A broad outline of the main steps involved in bridge maintenance management is given in Figure 4. It involves two main algorithms:

(a) to optimise maintenance costs taking account of the rate of deterioration
(b) to calculate the rate of deterioration and predict future condition

Possible algorithms for (b) will be discussed in section 3.8 of this deliverable. A possible algorithm for (a) is discussed here. The first step is to decide the maintenance strategy because this will substantially reduce the number of possible maintenance options. The approach is best explained by considering the tree diagram shown in Figure 5. Starting at year 0, which can correspond to any bridge age and condition, there will be a number of maintenance options (2 are shown in Figure 5) one of which is always 'do nothing'. Each maintenance option will have an associated cost so each branch of the tree will have a cost. The nodes at either end of a branch will have condition values representing the condition state before and after the maintenance work represented by the branch. These condition states are obtained using algorithm (b). Thus every node will have a condition state and a number of possible maintenance options represented by branches emanating to the right (increasing time). The optimisation process calculates the cost of each pathway through the tree and finds the pathway representing the lowest total cost. The cost of each pathway is simply the sum of the costs of each branch in the pathway discounting according to the time associated with each branch. In practice the number of pathways is very high (a three-option tree over 20 years would have 3^{20} pathways) and although the calculations are simple a large amount of computer time would be needed. Dynamic programming can be used to eliminate redundant pathways in order to reduce the number that need to be costed and thereby to reduce the computer time to a reasonable value.

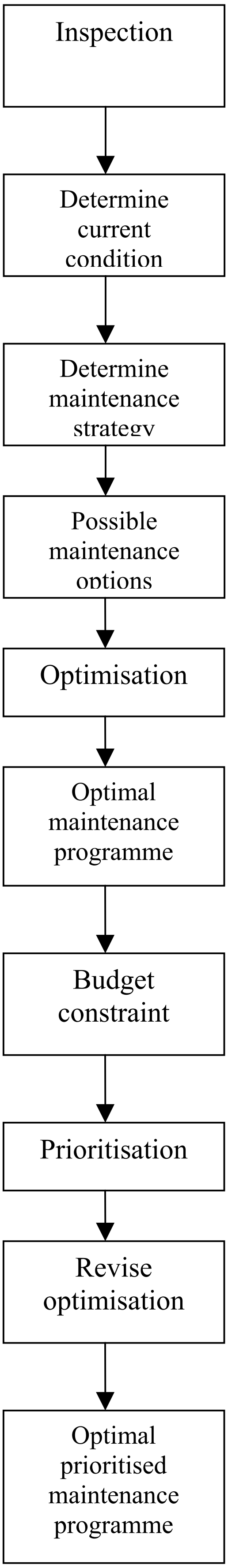
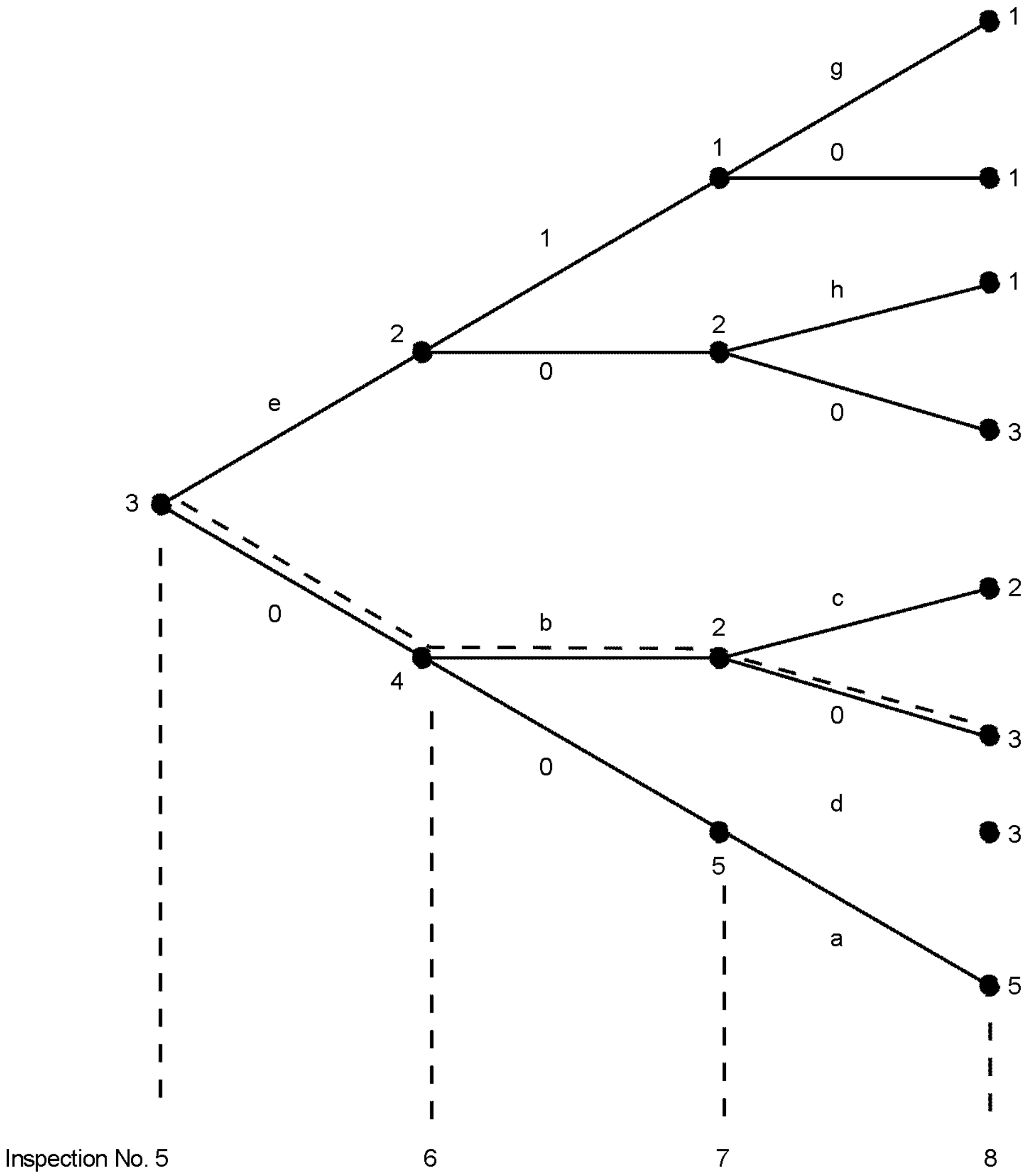


Figure 4: Main steps involved in bridge maintenance management



a	Traffic delay cost
b,..................h	Maintenance costs
1,2,3,4,5	Condition states
0	Zero maintenance cost (do nothing option)
– – – – –	Minimum cost pathway (b)

Figure 5: Optimisation tree diagram for two maintenance options per node

3.7 PRIORITISING MAINTENANCE WORK

There are many factors that can lead to a need for prioritisation such as:

- policy decision to prioritise a certain type of maintenance
- policy decision to prioritise maintenance on a particular route
- policy decision to provide insufficient funding to carry out the optimal maintenance strategy.

The latter is by far the most common reason for prioritisation since the demand for public expenditure always seems to exceed the supply of revenue. The limitation of the maintenance budget is in effect a constraint on the optimisation process and it can be dealt with in this way although it complicates the algorithm and requires more computer time. In practice simpler methods have been adopted. One simple approach has the objective of minimising the number of bridges that have outstanding optimal maintenance work. This would involve ranking bridges in order of increasing maintenance costs so the ones with lower costs have higher priority and the bridges with high maintenance costs would be deferred for consideration next year. The consequence of this approach is that bridges with high maintenance costs may never be maintained. Clearly this approach is unsatisfactory even though the objective on which it is based is reasonable. A prioritised maintenance programme is by its nature sub-optimal and will result in increased lifetime costs and traffic disruption. A better approach to prioritisation is to minimise these consequences. The steps involved in such an approach are as follows:

(i) In a given year form a subset of the bridge stock containing only those bridges requiring maintenance according to the optimal maintenance programme.

(ii) Assume for each bridge in the subset that the optimal maintenance work is deferred and call the resulting cost saving for a bridge the benefit.

(iii) Produce a new optimal maintenance programme for each bridge based on the assumption in (ii).

(iv) Calculate the increases in lifetime cost and traffic disruption for each bridge resulting from applying the assumption in (ii) and call this the cost of prioritisation for the bridge.

(v) Calculate the cost benefit ratio for each bridge and rank the bridges in the subset in order of increasing value of this ratio.

(vi) The bridge with the lowest cost and highest benefit will have the smallest ratio value and thus the highest priority for maintenance; this bridge will be selected for maintenance in the given year and removed from the subset.

(vii) Repeat step (vi) until the maintenance budget is consumed.

(viii) The bridges remaining in the subset when the budget is consumed will have their maintenance work deferred and will be considered for maintenance when it next becomes optimal.

In practice the above prioritisation process would only apply to bridges requiring non-essential maintenance. All bridges requiring strengthening or replacement would have the highest priority and this work would be carried out before the non-essential work was prioritised.

This prioritisation procedure is useful because it is objectively based. It does not consider subjective factors such as the environment, sociology, sustainability, aesthetics or historical value. These should be considered qualitatively by local engineers using engineering judgement to decide if the ranking of bridges should be modified.

Another approach to prioritisation is to consider all the factors affecting the priority and to combine them in some way to produce a priority index that can be used to rank the bridges (Deliverable D12). This is a much simpler approach but suffers from subjectivity and hence possible bias concerning the values of some parameters and in the formula combining them. Subjective factors include the importance of the road, historical value and aesthetics. Objective factors include condition state, cost of maintenance, life of maintenance, life required and safety index.

The prioritisation process can have a profound influence on the maintenance programme and necessitates considerable care in order to minimise lifetime costs and disruption to traffic.

This is described in detail in Deliverable D12 and the proposed methodology is divided into three levels as shown in Figure 6.

The first level of prioritisation is a ranking of bridges based on their condition rating that is based on the classification of condition into a number of classes. The purpose is to select the most damaged bridges having a condition rating above a given critical value. If enough funds are available, the bridges with a condition rating above the given critical value are repaired. In most cases however, the budget is limited, and it is not possible to maintain all of those bridges so a second level of prioritisation is necessary.

The second level of prioritisation is a priority ranking function R_A which takes into account the condition of the bridge (R_C), the Safety Index of the bridge (β), the remaining service life (S_L) and the impact of the bridge on the road network (I_F). The Impact Factor takes into account the importance and functionality of the bridge, and is a function of road classification, traffic, location and historical value. The estimation of the remaining service life is based on engineering judgement. A fifth parameter, the seismic resistance of the structure, may be added in regions of seismic activity.

The model for ranking is therefore usually based on a function of the four parameters:

$$R_A = f\ (R_C, \beta, S_L, I_F)$$

A database containing sufficient empirical data is needed on a finite sample of ranked bridges in order to initiate the process. The CAE method is then used to predict the output variable R_A for a given bridge from the known input variables (R_C, β, S_L, I_F) by taking into account the known relations between input and output variables of the sample of bridges. The CAE method is an optimisation method, which can incorporate a knowledge-learning process or a neural network approach and requires a database containing sufficient, empirical data on a finite sample of the ranked bridges.

At the end of the process, a priority ranking of all bridges is obtained, but engineering judgement is still needed because all the constraints may not be considered (eg political decisions, urgent intervention for ensuring traffic safety, etc).

The third level of prioritisation is based on a maintenance optimisation for different selected maintenance strategies, taking into account the costs for each selected strategy. The optimisation is made for a particular bridge (project level optimisation) and then, for the whole stock (network level optimisation). The stock of bridges studied may be limited to the selected number of bridges resulting from the second level of prioritisation.

Project level optimisation involves an economic evaluation of each maintenance option and should take into account the total cost including both direct costs of repair and indirect costs (administrative costs, user delay costs, width restriction costs, etc.). The optimal maintenance strategy for a bridge, over a period $t - t_o$, is the one for which the amount of money saved by deferring maintenance work in current year is comparatively high compared with the long term costs due to the additional deterioration occurring during the period. This method is also called cost/benefit analysis, and the cost/benefit ratio, R, is expressed for a given bridge, for a chosen period $t - t_o$, and for a given maintenance option as:

$$R = \frac{\text{lifetime cost } + \text{ cost due to additional deterioration}}{\text{money saved by deferring maintenance work}}$$

The lower the ratio, the higher is priority for maintenance.

Network level optimisation uses the different values of the cost/benefit ratio obtained for all bridges to produce a ranking of bridges at the network level. This network level optimisation is an iterative process, which includes such factors as:

- available funds for maintenance of the whole bridge stock
- co-ordination of maintenance work for groups of bridges
- co-ordination of maintenance work on bridges with the maintenance work on the road
- political decisions
- natural disasters such as floods, earthquakes.

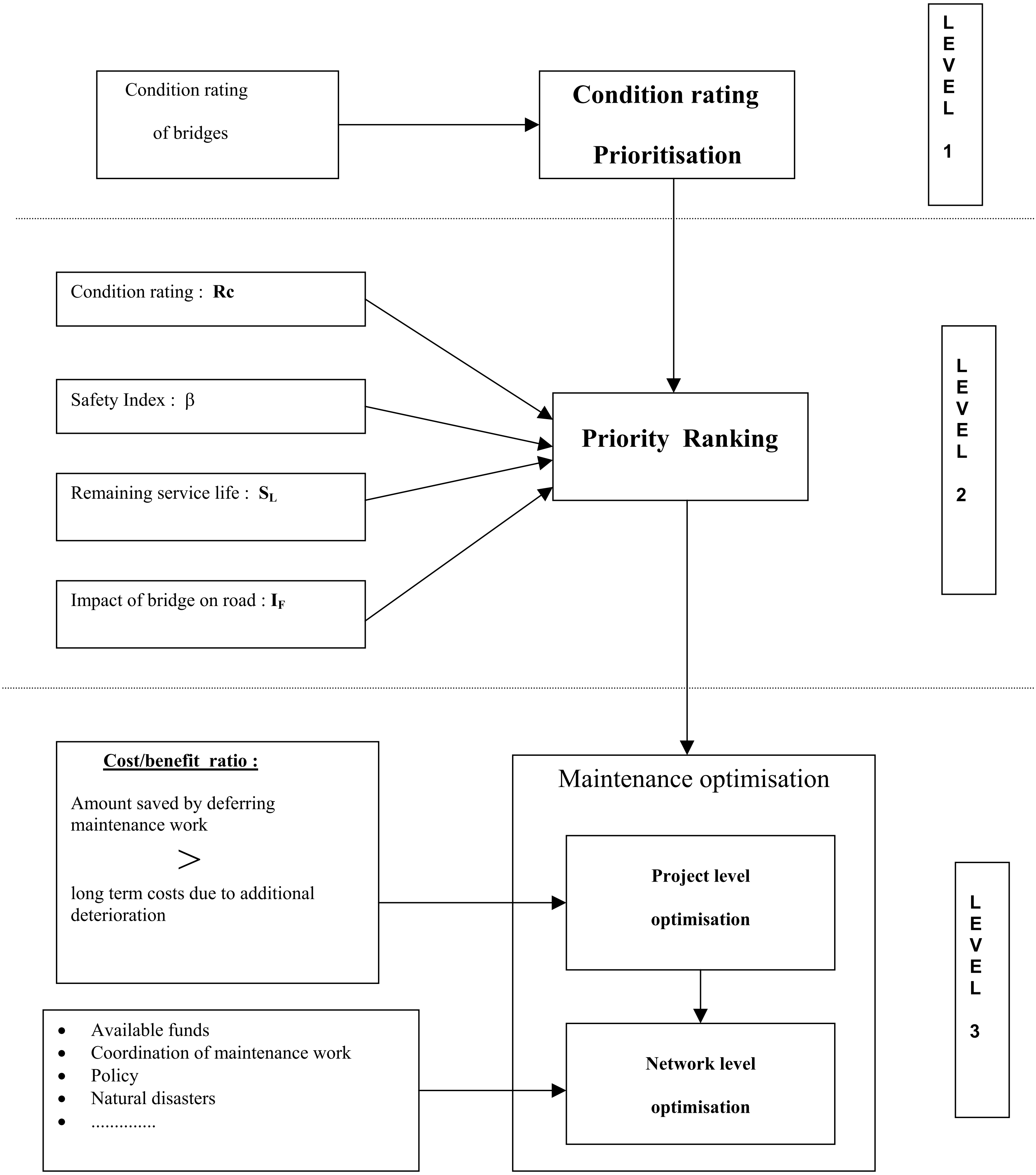


Figure 6: Scheme for prioritisation of bridge maintenance.

There are some common features between this approach and that described in Deliverable D7 and summarised above. The methodology described in Deliverable D7 is a global cost analysis for a given bridge, and it can be considered to be an alternative to the cost/benefit ratio method described above for the project level optimisation (third level). The two first levels described above are used to select a sub-set of the bridge stock on which maintenance prioritisation is to be carried out, to avoid having to apply the cost/benefit ratio to all bridges. Whichever method is chosen a network level optimisation is then required.

Limitations of knowledge on the subject make it difficult to give a preference between the global cost analysis and the cost/benefit ratio method in order to choose the best maintenance programme for a given bridge. An examination of the two methods shows that the first seems easier to apply and has the advantage of considering the whole life of the bridge. The second is intended to be used over a certain period of time and introduces the difficulty of needing to know the cost due to the additional deterioration, which requires the evolution of the deterioration process to be known with enough accuracy.

3.8 PREDICTION OF FUTURE DETERIORATION

It is clear from the preceding sections that a method for predicting future deterioration is a fundamental requirement for a BMS. A simple method is to conduct an extrapolation of the condition of a structure or its elements from the past data. This should be done on a homogeneous family of elements (like in the Pontis BMS), or on a homogeneous family of bridges (like in the French BMS). The French system considers the distribution of bridges in different condition classes as a function of their age over a period of seventy years and may be used to predict their future evolution. Many hypotheses should be made however, among them:

- changes in design and construction techniques have only a small influence on the durability
- continuity in the benefits of maintenance
- the absence of new causes of deterioration.

This method could be improved by switching from a deterministic analysis of the bridge transition among condition classes to a probabilistic analysis by introducing a Markov chain process and transition probabilities like in the Pontis BMS.

The probabilistic approach uses the condition state assessments made during bridge inspections. This information already exists and is cheap to collate. Measuring condition using the condition state assessments made by bridge inspectors is normally based on a set of discrete states that represent different stages in the deterioration process. There is a close association between the condition state and the appropriate type of maintenance, which simplifies the interpretation of the condition measure. Different materials have different deterioration processes hence it is necessary to set up a condition state scale for all the common deterioration processes and materials of construction. A condition state scale consists of a number of states each of which is given a numeric value and a definition describing the stage of the deterioration process. The number of states is normally between 3 and 10. If the assessment is based entirely on visual observations, the number of states normally lies at the lower end of this range, whereas more states can be used if non-destructive tests and material sampling are used. When too few states are used the deterioration process is not adequately described, but if too many states are used it becomes difficult to differentiate between them, resulting in different inspectors making different condition assessments on the same element. Deterioration sometimes results in the formation of latent defects and in these cases it is recommended that the condition state should be based on visual observations, non-destructive testing and sampling. An example of a typical condition state scale for corrosion of reinforced concrete is shown in Table 4.

The general procedure is as follows:

(i) Sub-divide the bridge stock into sets of bridge elements with characteristics that indicate that they should deteriorate by similar mechanisms. Factors that are most likely to influence the deterioration process are the construction material, geographic location and when and how the element was previously maintained. As more information is obtained about deterioration processes the sub-division can be refined with the proviso that the number of bridges in each set is statistically significant.

(ii) the average condition state as a function of age usually fits quite well to a polynomial equation such as:

$$C(t) = a + bt + ct^2 + dt^3$$

where $C(t)$ is the average condition state of the stock at time t years and a, b, c, d are polynomial coefficients

(iii) The beginning of the Markov Chain is represented by the tree diagram shown in Figure 7. The numbers at the nodes represent the condition state and the numbers associated with the branches of the tree such as p_{xy} represent the transition probability of going from state x to state y between consecutive inspections. Note the simplifying assumptions:

$$y \geq x \quad \text{and} \quad y = x \quad \text{or} \quad y = x + 1$$

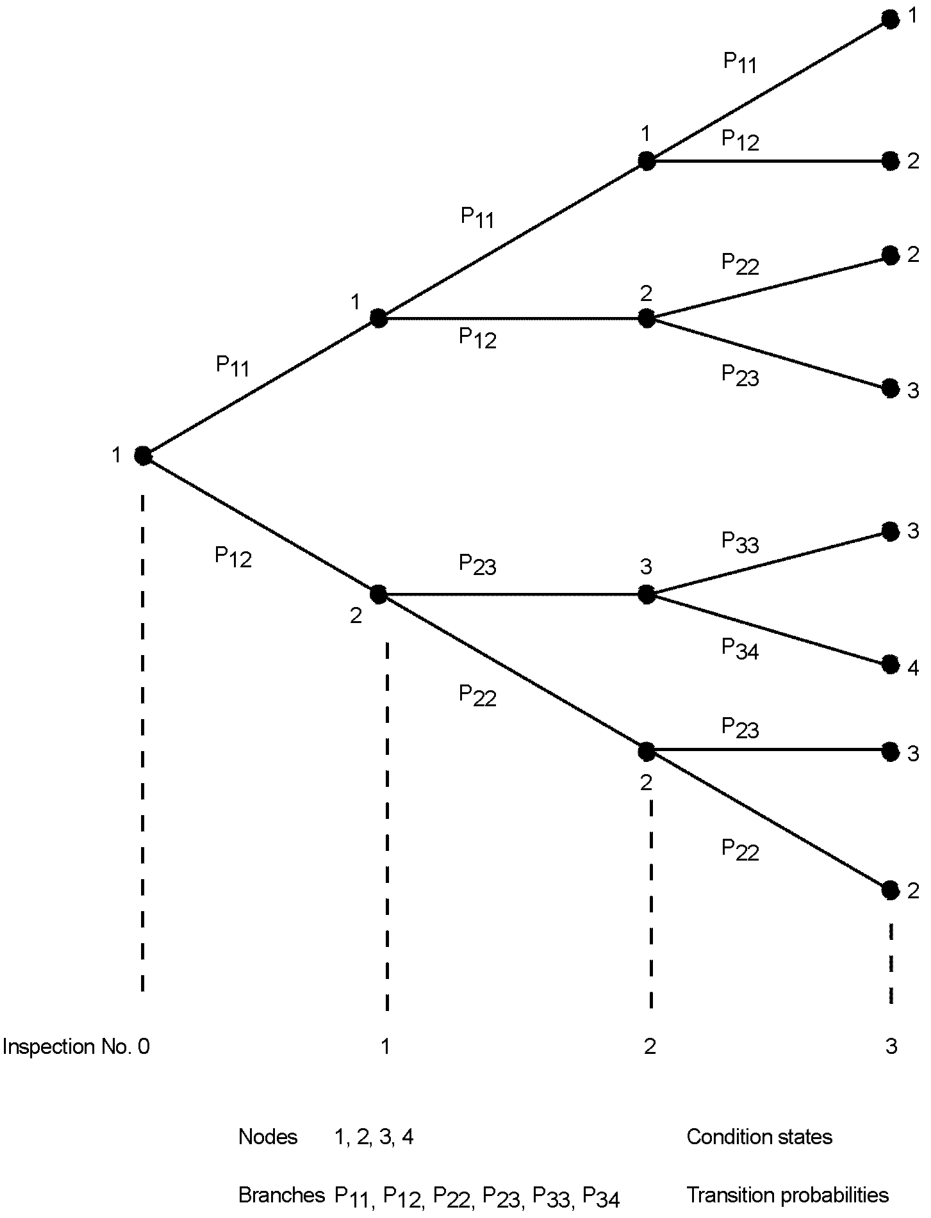


Figure 7: Markov chain diagram

This diagram can be used to determine the probability of being in a given state at a given time and to determine the average condition state at a given time.

(a) probability of being in state 2 at the second inspection is given by $p_{11}\, p_{12} + p_{12}\, p_{22}$

and

(b) the average condition state at the second inspection is given by

$$C_m(t,w) = p_{11}^2 + 2(p_{11}\, p_{12} + p_{12}\, p_{22}) + 3\, p_{12}\, p_{23}$$

where C_m (t,w) is the average condition state at time t determined by the Markov Chain. The set of transition probabilities is denoted by w.

Thus in order to find C_m (t,w) it is necessary to know the values for p_{11}, p_{22}, p_{33} and p_{44}.

3.9 A FRAMEWORK FOR A EUROPEAN BMS

A bridge management system that is able to answer the various objectives of the managers must be modular and must incorporate, at least, the following principal modules:

1. Inventory of the stock
2. Knowledge of bridge and element condition and its variation with age
3. Evaluation of the risks incurred by users (including assessment of load carrying capacity)
4. Management of operational restrictions and of the routing of exceptional convoys
5. Evaluation of the costs of the various maintenance strategies
6. Forecast the deterioration of condition and the costs of various maintenance strategies
7. Socio-economic importance of the bridge (evaluation of the indirect costs)
8. Optimisation under budgetary constraints
9. Establishment of maintenance priorities
10. Budgetary monitoring on a short and long-term basis

Figure 8 presents an architectural framework of a BMS including these principal modules with their main interactions. The framework takes into account the two levels of management (project level and network level) and is organised in order to show the contribution of each of the BRIME Work Packages (WP 1 to WP 6).

3.9.1 Framework

The interrelationships between the BMS inputs, models and outputs are very complex as indicated by Figure 8. It would be difficult to produce a flow chart for the entire BMS using full names for inputs, outputs and models. There would be numerous intersections and the chart would quickly become very complicated to follow. Instead of a full flow chart the BMS has been broken down into various models and the inputs and outputs have been given for each model (Tables 5 and 6). The inter-connections between different models are explained in terms of outputs of models which act as derived inputs for another model (Table 7). The interconnections can also be seen in Figure 8 although the key for the codes for outputs, models and inputs will have to be used in order to interpret the framework. It is possible to traverse the framework starting at the output to find all the inputs required for the model. The models have been divided into project and network level models.

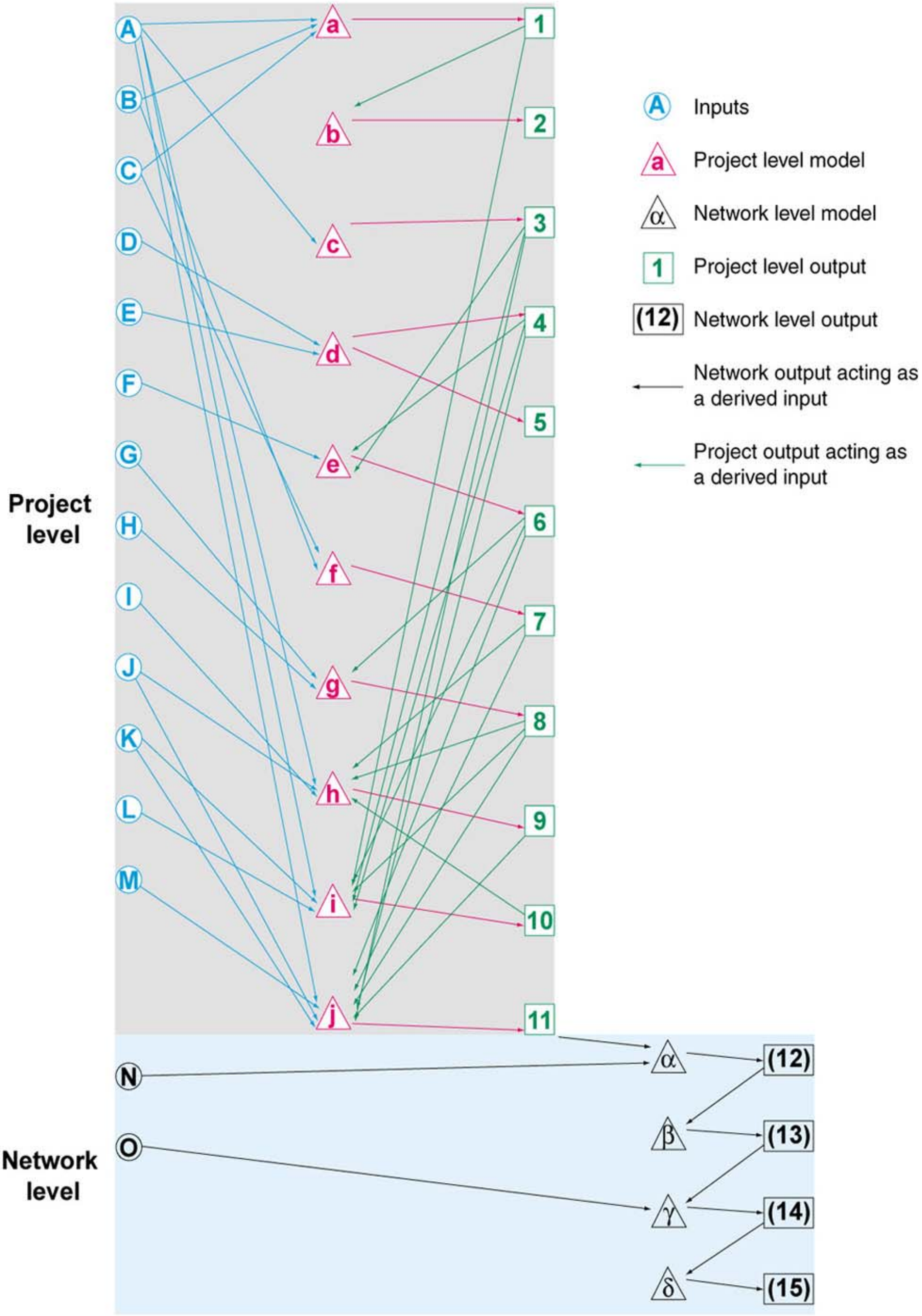


Figure 8: Interconnections between inputs, models and outputs for BMS

3.9.2 Models: (a to j) Project Level and (α to δ) Network Level

a. To use inspection observations, material testing and information in the inventory to derive a measure for the condition of each structural element and component of the bridge.

b. To combine the condition state values for all elements and components to provide a measure for the overall condition state of a bridge.

c. To use information in the inventory such as structural design calculations and as-built drawings to find the original load carrying capacity measured in terms of load, reduction factor or reliability index. The most structurally vulnerable parts of the bridge would also be identified.

d. The inspection and test histories for the particular bridge under investigation, and for all the other bridges in the stock with similar characteristics would be used to investigate the rate of deterioration and to predict how the condition of particular elements and the entire bridge would vary in the future. This variation with time could be represented as a condition state-time trajectory where a discrete condition state is associated with each year or some other agreed interval.

e. The purpose of this model is to predict the need for essential maintenance when the strength of the bridge becomes inadequate i.e. the bridge becomes sub-standard. This has always been difficult to achieve. The approach could be based on the following inputs.

   - the latest load carrying capacity
   - the structurally vulnerable parts of the bridge
   - the condition state-time trajectory for the vulnerable parts
   - information from the assessment history of the bridge.

   Note that the first three inputs are outputs from other models (these have been called derived inputs) whereas the last input is an original input.

   An estimate of the time when essential maintenance will become necessary can then be based on the original or latest assessment of capacity and the rate of deterioration near the vulnerable areas. If the capacity is only slightly greater than the minimum acceptable value, the bridge may become substandard in the future due to changes in loading even if the vulnerable areas are not deteriorating.

f. The cause of deterioration has a bearing on the maintenance methods that are effective in a given situation and may also influence the maintenance strategy. The extent of deterioration can also affect the choice of maintenance method and strategy; it will directly influence the cost of maintenance.

   The information from inspections and tests can be used to establish the cause and extent of deterioration.

g. Maintenance work and traffic restrictions to substandard bridges can result in disruption and delays to road users, which have an economic cost. These costs can be calculated using traffic data such as traffic composition, vehicles per day and traffic growth rate, the duration of restriction and the type of vehicles needing to be re-routed. The latter can be obtained from assessment results. The impact of traffic disruption can influence the choice of maintenance method and strategy.

h. The optimal maintenance method selected for a bridge should, subject to various constraints, minimise the lifetime cost of the bridge. In other words if a different maintenance method was used the lifetime cost would be greater. The choice of maintenance method will depend on:

   - information from the inventory such as access and repairability
   - the maintenance strategy adopted
   - the delay costs resulting from different types of maintenance
   - the cause and extent of deterioration
   - the required life, free from maintenance after the work is completed
   - the costs and lives of different maintenance methods

i. The choice of maintenance strategy has an important bearing on the life of a bridge and the whole life cost. Maintenance strategies include replacement, strengthening, rehabilitation, repairs, preventative maintenance and do nothing. The primary distinctions are based on the condition and strength of the bridge. If the bridge is substandard due to insufficient load carrying capacity or falling masonry/concrete for example then essential maintenance is required. It is essential in the sense that if the maintenance is not done traffic restrictions must be imposed to make the bridge safe for users. It can be seen that the requirement for an essential maintenance strategy such as strengthening or replacement depends on safety rather than cost. If a bridge is not substandard, but has undergone considerable deterioration, rehabilitation or repairs are likely to be the chosen strategy. In this case the need for maintenance is based on reducing the lifetime cost by increasing the age of the bridge when essential maintenance eventually becomes necessary or by avoiding the need for essential maintenance altogether. Preventative maintenance is a possible strategy when deterioration has not yet occurred to a significant extent; it should reduce the rate of deterioration and lifetime costs. The choice of strategy can also depend on the element involved and other site specifics that would be recorded in the inventory. In particular the choice of maintenance strategy will depend on:

   - the current condition state for the elements and bridge
   - the load carrying capacity and critical parts
   - information in the inventory
   - required future life of bridge
   - condition state-time trajectory for each element
   - date when essential maintenance will become necessary
   - delay costs associated with different strategies
   - maintenance history and policy

j. An ultimate objective of a BMS is to establish an optimal maintenance programme for each bridge (project level) which will predict the timing and type of maintenance required to achieve both the safe operation of the bridge and a minimum life time cost. The optimisation will have to take account of the following factors:

- information in the inventory
- the choice of optimal maintenance method
- maintenance costs and lives
- delay costs
- the rate of deterioration (condition state-time trajectories)
- the life required of the bridge
- the extent of deterioration
- the date when essential maintenance becomes necessary
- the discount rate used in lifetime costing.

The first ten models are involved with analysing data and making decisions about the maintenance of particular bridges - project level bridge management. The next four models (α-δ) analyse and make decisions about a stock of bridges - network level bridge management. The bridges chosen to be within the stock can depend on many factors such as

- geographical region
- type of road –national roads, minor roads etc
- type of bridge – overbridge/underbridge

For various reasons it may not be possible or convenient to carry out the optimal maintenance work for each bridge. For example there may be insufficient funds or labour and efficiency can sometimes be improved for the network as a whole by deferring or bringing forward maintenance for particular bridges in order to co-ordinate the work and reduce traffic disruption. These considerations place constraints on the optimisation process of which the following are common examples:

- budget
- network efficiency
- policy

A constrained optimisation process produces an optimal maintenance programme subject to the constraints imposed. This is, of course, sub-optimal compared with the unconstrained optimisation. It has been found that the available funding for bridge maintenance is almost always insufficient to carry out all the work identified in the unconstrained optimisation. Thus the work needs to be prioritised in such a way as to minimise the whole life cost subject to limited funds being available each year. It is important that prioritisation should not affect safety hence bridges needing essential maintenance must be satisfactorily maintained or traffic restrictions imposed. The problem with prioritisation when it continues over many years is that the number of substandard bridges will progressively increase resulting in continuously decreasing funds for non-essential maintenance, thereby creating a vicious circle.

The purpose of optimisation and prioritisation processes is to ensure that the money spent on bridge maintenance achieves the best value. In practice these bridge management techniques are usually first applied to a bridge stock that already has a significant number of substandard or deteriorated bridges. The manager may therefore not only want to ensure that his expenditure is achieving the best value, but also that policy targets for the condition of the stock and individual bridges are also being satisfied. Such policy target parameters may include the following:

- number of bridges with load restrictions of different degrees
- number of bridges with other traffic restrictions
- number of substandard bridges
- annual traffic delay costs due to restrictions and maintenance works
- number of bridges overdue an inspection
- number of replacements each year
- average condition of the stock
- number of bridges with condition state greater than X
- number of bridges containing one or more elements with a condition state greater than Y

The manager or owner will set targets based on these parameters so that he can monitor, each year, the safety, condition and disruption caused by the operation of the bridge stock.

These models monitor the implications of a given maintenance programme and budget and compare these with the policy parameter targets to find the degree of compliance. If the compliance is low it indicates that the budget is insufficient to achieve the targets and that it must be increased or the targets reduced. The final model estimates the budget needed in order to achieve a specific degree of compliance with the targets.

3.9.3 Basic inputs

A Inventory
B Inspection
C Test Data
D Inspection history
E Test history
F Assessment history
G Traffic data
H Duration of restriction
I Future maintenance free life (MFL) of repair
J Compendium of maintenance life/costs
K Future life required
L Maintenance history/policy
M Discount Rate
N Constraints
O Policy Parameter Targets

3.9.4 Calculations

a	Condition state of element	]	
B	Condition state for bridge	]	
c	Assessment of LCC assuming no deterioration	]	P
d	Rate of deterioration/prediction future condition	]	R
e	Predict future LCC	]	O
f	Cause/extent of deterioration	]	J
g	Traffic delays	]	E
h	Optimal maintenance method	]	C
i	Decide maintenance strategy	]	T
j	Optimal maintenance programme	]	

α	Prioritisation model	]	N
β	Implication model	]	E
δ	Comparison model	]	T
γ	Budget variation model	]	W
			O
			R
			K

3.9.5 Project outputs

1. Current condition state (elements)
2. Current condition state (bridge)
3. Original LCC and Critical areas
4. Condition state/time trajectory for each element
5. Condition state/time trajectory for bridge
6. Date for essential maintenance
7. Cause/extent of deterioration
8. Delay costs due to maintenance or restrictions
9. Optimum maintenance method
10. Best maintenance strategy
11. Optimal maintenance programme
12. Prioritised maintenance programme
13. Values of policy parameters
14. Degree of compliance with policy parameter targets
15. Budget needed to obtain say 90% compliance

Table 5
Project level BMS

Model	Input	Calculation	Output	Work package
a	Inventory, Inspection, Test data	Condition state of element	Current condition state of element	1
b	*Current condition state of element*	Condition state for bridge	Current condition state for bridge	1
c	Inventory	Original LCC for bridge	Original LCC + critical areas	2
d	Inspection history Test history	Rate of deterioration	CS time trajectory for element	4
		Prediction of future condition	CS time trajectory for bridge	4
e	Assessment history *CS time trajectory for elements/critical areas*	Predict future LCC	Date for essential maintenance	3
f	Inspection test data	Cause/extent of deterioration	Cause & extent of deterioration	5
g	Traffic data Duration restriction Load restriction	Delay model	Delay costs due to maintenance restrictions	5
h	Inventory *Delay costs* *Cause/extent of deterioration* Future MFL needed Maintenance strategy Maintenance costs / lives	Optimal maintenance method	Optimal maintenance method	5
i	Inventory Future life required *Current CS for elements* *CS trajectory for elements* *Date for essential maintenance* *Delay costs* Maintenance history/ policy *LCC and critical areas*	Decide maintenance strategy	Best maintenance strategy	5
j	Inventory Optimal maintenance method Maintenance cost/ lives Delay Costs Condition state time trajectory for elements Life required for bridge *Extent of deterioration* *Time for essential maintenance* Discount rate	WLC / optimisation	Optimal work programme	6

Italic = Project Level Output
LCC = Load carrying capacity
MFL = Maintenance free life
CS = Condition state

Table 6
Network level BMS

Model	Input	Calculation/ Assessment	Output	Work package
α.	*Optimal maintenance programme for each bridge* **Constraints such as budget, political**	Prioritisation model	Prioritised maintenance programme giving dates and types of maintenance	6
β.	Prioritised maintenance programme	Implication model	Values of policy parameters each year	7
γ.	Values of policy parameters **Policy parameter targets**	Comparison model	Degree of compliance with policy parameter targets each year	7
δ.	Degree of compliance	Budget Variation model	Budget needed to satisfy say 90% of policy targets	7

For the input column of Table 6

Italics = Project level output
Bold Text = Network level inputs
Verdana Font = Network level outputs

NOTE When an output acts as an input for another model it is assumed that inputs for that output in the previous model are also inputs for the new model.

For example in model 4 the degree of compliance input was the output of model 3 and the inputs for model 3, the value of the policy parameters and the policy parameter targets, are therefore also inputs of model 4. Traversing backwards in this way can be used to find the primary inputs and model interconnections. For example the policy parameter targets are a primary input.

Table 7
Inputs associated with outputs (see Figure 8)

OUTPUT	DERIVED INPUTS	BASIC INPUTS
1		A, B, C
2	1	
3		A
4		D
5		E
6	3, 4	F
7		B, C
8	6	G, H
9	7, 8, 10	A, I, J
10	1, 3, 4, 6, 8	A, K, L
11	4, 3, 8, 9, 7, 6	A, J, K, M
(12)	11	N
(13)	(12)	
(14)	(13)	O
(15)	(14)	

All the inputs associated with a given output can easily be obtained from this Table. For example the inputs associated with output 6 are F, A and D where A and D are derived inputs obtained from outputs 3 and 4. In Table 7, the derived inputs for a given output are themselves inputs.

4 CONCLUSIONS

This report has shown how results from the main bridge management activities such as inspections, assessments, testing, maintenance, prioritisation and replacement, can be combined to produce a framework for a computerised bridge management system that will provide both project and network level information. The types of project level information generated include:

- measures of the condition of each structural element and component of a bridge and for the complete bridge
- the load carrying capacity of a bridge and its most structurally vulnerable parts
- the rate of deterioration of elements and components of a bridge enabling their future condition to be predicted
- predictions of when a bridge will become substandard in terms of the load carrying capacity
- identification of the maintenance requirements of a bridge
- guidance on effective maintenance strategies and methods
- programmes of maintenance work indicating the timing of specified maintenance methods needed in order to minimise the whole life cost of a bridge.

The types of network level information generated include:

- prioritised programmes of maintenance when the optimisation of the programme is constrained by factors such as a maintenance budget that is insufficient to enable all the work in the optimal programme to be carried out
- values of policy target parameters such as (a) the number of bridges with load restrictions at a given date, (b) the number of bridge replacements each year and (c) the average condition of bridges in the stock at a given date
- degree of compliance of measured policy target parameters with set benchmark values
- size of maintenance budget needed to achieve a specified degree of compliance.

Whilst the system was developed for the European Road network, it could also be applied to national and local road networks.

Ultimately it should be possible to combine management systems for pavements, earthworks, bridges (structures) and street furniture to achieve a route management system.

5 BIBLIOGRAPHY

Al-Subhi K et al (1989). *Optimising system level bridge maintenance rehabilitation and replacement decisions*. FHWA/ NC 89-002, Washington DC.

Bungey J H (1982). *Testing of concrete in structures*. Surrey University Press, Glasgow.

Darby J J, Brown P and P R Vassie (1996). *Bridge management systems : The need to retain flexibility and engineering judgement*. Bridge management 3*,* 212-218, E and FN Spon, London.

Das P (1996). *Bridge Management Objectives and Methodologies*. *Bridge Management 3.* 1-7, E and FN Spon, London.

Das P (1998). *Development of a comprehensive structures management methodology for the Highways Agency*. The management of Highway Structures Conference, Institution of Civil Engineers, London.

Department of Transport (1993). *Bridge Inspection Guide.* HMSO, London.

Department of Transport (1982). Quadro 2 User Manual. London.

ENPC (1992). *Gestion des ouvrages d'art.* Actes du colloque organisé par l'ENPC, Paris, 18-20 Octobre 1994, Presses de l'ENPC, pp596.

Federal Highways Administration (1987). *Bridge management Systems.* FHWA DP-71-01, Washington DC.

Frangopol D M and Estes A L (1997). *Lifetime bridge maintenance strategies based on system reliability*. Structural Engineering International IABSE*,* 1997, 7 (3), 193-198.

Gusella V et al (1996). *Information System for the management of bridge owned by the province of Perugia*, Italy. Bridge Management 3*,* 592-602, E and FN Spon, London.

Harding J E et al (ed) (1990). *Bridge Management: Inspection, Assessment, Maintenance and Repair*, E and FN Spon, London.

Harding J E et al (ed) (1993). *Bridge Management 2*, London.

Harding J E et al (ed) (1996). *Bridge Management 3*, Thomas Telford, London..

Highways Agency (1994). Inspection of Highway Structures. BA63/94. *Design Manual for Roads and Bridges Volume 3*, HMSO, London.

Highways Agency (1997). *The Assessment of highway bridges and structures. BD 21/97 and BA 16/97*. Design Manual for, Roads and Bridges Volume 3 / Section 4, London, HMSO.

Hogg V and Middleton C P (1998). *Whole life performance profiles for highway structures*. The management of highway structures conference, Institution of Civil Engineers, London.

Service d'Etudes Techniques des Routes et Autoroutes (1996). *Image de la Qualité des Ouvrages d'Art (IQOA): Méthodologie, Procès-verbaux de visite, catalogues de désordres, et valise de formation.* France.

Institution of Civil Engineers (1998). *Supplementary load testing of bridges.* Thomas Telford, London. pp 59-63.

Institution of Civil Engineers (1998). *The Management of Highway Structures.* Conference Proceedings, Institution of Civil Engineers. London.

Ministère des Transports (1995) *Instruction Technique pour la Surveillance et l'Entretien des Ouvrages d'Art – 1ère partie : dispositions applicables à tous les ouvrages.* Direction des Routes et de la Circulation Routière, France, 19 octobre 1979 (révisée le 26 décembre 1995)

Llanos J (1992). *La maintenance des ponts, Approche économique.* Presses de l'ENPC, 176 pages.

Jiang Y and Sinha K C (1989). *A dynamic optimisation model for bridge management systems*. Transportation Research Board annual meeting, Paper no. 88-0409, Washington DC.

Jiang Y et al (1989). *Bridge performance prediction model using the Markov Chain*. Transportation Research Record No. 1180, TRB, Washington.

Kreugler J et al (1986). *Cost effective bridge managemnet strategies*. FHWA/ RD-86/ 109, Washington DC.

OCDE (1992). *La gestion des ouvrages d'art.* Paris. pp132.

Odent N, Berthellemy J and Delfosse G (1999). *Impact d'une politique de gestion sur l'état d'un partrimoine d'ouvrages en béton armé.* Ouvrages d'Art No. 33, Service d'Etudes techniques des Routes et Autoroutes, décembre.

OECD. (1981). *Bridge Maintenance.* OECD, Paris.

Robichon Y, Binet C and B Godart (1995). *IQOA: Evaluation of bridge condition for a better maintenance policy.* Symposium international de l'AIPC « Extended the lifespan of structures », San Francisco, 23-25 août 1995.

Saito M and Sinha K (1990). *Timing for bridge replacement, rehabilitation and maintenance*. Transportation Research Board annual meeting, Paper no. 890336, Washington DC.

Shetty N K et al (1996). *A risk based framework for assessment and prioritisation of bridges*. Bridge management 3, 571-579, E and FN Spon, London.

Spackman M (1991). *Discount rates and rates of return in the public sector : Economic Issues*. Govt Econ service working paper No. 113, HM Treasury.

Sundararajan C R (1995). *Probilistic Structural Machanics Handbook*. Chapman and Hall, London.

US Department of Transportation, Federal Highways Administration (1988). *Recording and coding guide for the structure inventory and appraisal of the nations bridges*. FHWA-ED-89-044, Washington DC.

Vassie P R and Rubakantha S (1996). *A model for evaluating the whole life cost of concrete bridges*. Corrosion of reinforcement in concrete construction*,* 156-165, Society for Chemical Industry.

Winston W L (1991). Operations Research. PWS – Kent, Boston.