1

PM-1 3 1/2" x 4" PHOTOGRAPHIC MICROCOPY TARGET
NBS 1010a ANSI/ISO #2 EQUIVALENT

PRECISIONSM RESOLUTION TARGETS

National Library
of Canada

Acquisitions and
Bibliographic Services Branch

395 Wellington Street
Ottawa, Ontario
K1A 0N4

Bibliothèque nationale
du Canada

Direction des acquisitions et
des services bibliographiques

395, rue Wellington
Ottawa (Ontario)
K1A 0N4

Your file / Votre référence

Our file / Notre référence

NOTICE

The quality of this microform is heavily dependent upon the quality of the original thesis submitted for microfilming. Every effort has been made to ensure the highest quality of reproduction possible.

If pages are missing, contact the university which granted the degree.

Some pages may have indistinct print especially if the original pages were typed with a poor typewriter ribbon or if the university sent us an inferior photocopy.

Reproduction in full or in part of this microform is governed by the Canadian Copyright Act, R.S.C. 1970, c. C-30, and subsequent amendments.

AVIS

La qualité de cette microforme dépend grandement de la qualité de la thèse soumise au microfilmage. Nous avons tout fait pour assurer une qualité supérieure de reproduction.

S'il manque des pages, veuillez communiquer avec l'université qui a conféré le grade.

La qualité d'impression de certaines pages peut laisser à désirer, surtout si les pages originales ont été dactylographiées à l'aide d'un ruban usé ou si l'université nous a fait parvenir une photocopie de qualité inférieure.

La reproduction, même partielle, de cette microforme est soumise à la Loi canadienne sur le droit d'auteur, SRC 1970, c. C-30, et ses amendements subséquents.

DEVELOPMENT OF OPTIMAL STRATEGIES FOR BRIDGE MANAGEMENT SYSTEMS

by

Hosny Abbas Hosny Mohamed

B.Sc., Cairo University, Egypt
M.A.Sc., University of Waterloo, Canada

A thesis submitted to the
Faculty of Graduate Studies and Research
in partial fulfilment of the requirements
for the degree of
Doctor of Philosophy
in
Civil Engineering

Department of Civil and Environmental Engineering
Carleton University
Ottawa, CANADA

The Doctor of Philosophy in Civil Engineering
is a joint program with the University of Ottawa, administered by
the Ottawa-Carleton Institute for Civil Engineering

@ Hosny Mohamed, 1995

National Library
of Canada

Acquisitions and
Bibliographic Services Branch

395 Wellington Street
Ottawa, Ontario
K1A 0N4

Bibliothèque nationale
du Canada

Direction des acquisitions et
des services bibliographiques

395, rue Wellington
Ottawa (Ontario)
K1A 0N4

Your file / Votre référence

Our file / Notre référence

The author has granted an irrevocable non-exclusive licence allowing the National Library of Canada to reproduce, loan, distribute or sell copies of his/her thesis by any means and in any form or format, making this thesis available to interested persons.

L'auteur a accordé une licence irrévocable et non exclusive permettant à la Bibliothèque nationale du Canada de reproduire, prêter, distribuer ou vendre des copies de sa thèse de quelque manière et sous quelque forme que ce soit pour mettre des exemplaires de cette thèse à la disposition des personnes intéressées.

The author retains ownership of the copyright in his/her thesis. Neither the thesis nor substantial extracts from it may be printed or otherwise reproduced without his/her permission.

L'auteur conserve la propriété du droit d'auteur qui protège sa thèse. Ni la thèse ni des extraits substantiels de celle-ci ne doivent être imprimés ou autrement reproduits sans son autorisation.

ISBN 0-612-08848-0

Canada

Name HUSNY A. McHAHAMED

Dissertation Abstracts International is arranged by broad, general subject categories. Please select the one subject which most nearly describes the content of your dissertation. Enter the corresponding four-digit code in the spaces provided.

CIVIL Engineering

SUBJECT TERM

0543

SUBJECT CODE

U·M·I

Subject Categories

THE HUMANITIES AND SOCIAL SCIENCES

COMMUNICATIONS AND THE ARTS

Architecture 0729
Art History 0377
Cinema 0900
Dance 0378
Fine Arts 0357
Information Science 0723
Journalism 0391
Library Science 0399
Mass Communications 0708
Music 0413
Speech Communication 0459
Theater 0465

EDUCATION

General 0515
Administration 0514
Adult and Continuing 0516
Agricultural 0517
Art 0273
Bilingual and Multicultural 0282
Business 0688
Community College 0275
Curriculum and Instruction 0727
Early Childhood 0518
Elementary 0524
Finance 0277
Guidance and Counseling 0519
Health 0680
Higher 0745
History of 0520
Home Economics 0278
Industrial 0521
Language and Literature 0279
Mathematics 0280
Music 0522
Philosophy of 0998
Physical 0523

Psychology 0525
Reading 0535
Religious 0527
Sciences 0714
Secondary 0533
Social Sciences 0534
Sociology of 0340
Special 0529
Teacher Training 0530
Technology 0710
Tests and Measurements 0288
Vocational 0747

LANGUAGE, LITERATURE AND LINGUISTICS

Language 0679
General 0289
Ancient 0290
Linguistics 0291
Modern 0291
Literature 0401
General 0294
Classical 0295
Comparative 0297
Medieval 0298
Modern 0316
African 0591
American 0305
Asian 0352
Canadian (English) 0355
Canadian (French) 0593
English 0311
Germanic 0312
Latin American 0315
Middle Eastern 0313
Romance 0314
Slavic and East European 0314

PHILOSOPHY, RELIGION AND THEOLOGY

Philosophy 0422
Religion 0318
General 0321
Biblical Studies 0319
Clergy 0320
History of 0322
Philosophy of 0469
Theology 0469

SOCIAL SCIENCES

American Studies 0323
Anthropology 0324
Archaeology 0326
Cultural 0327
Physical 0327
Business Administration 0310
General 0272
Accounting 0770
Banking 0454
Management 0338
Marketing 0385
Canadian Studies 0385
Economics 0501
General 0503
Agricultural 0505
Commerce Business 0508
Finance 0509
History 0510
Labor 0511
Theory 0358
Folklore 0366
Geography 0351
Gerontology 0578
History 0578
General 0578

Ancient 0579
Medieval 0581
Modern 0582
Black 0328
African 0331
Asia, Australia and Oceania 0332
Canadian 0334
European 0335
Latin American 0336
Middle Eastern 0333
United States 0337
History of Science 0585
Law 0398
Political Science 0615
General 0616
International Law and Relations 0617
Public Administration 0617
Recreation 0814
Social Work 0452
Sociology 0626
General 0627
Criminology and Penology 0938
Demography 0631
Ethnic and Racial Studies 0628
Individual and Family Studies 0629
Industrial and Labor Relations 0630
Public and Social Welfare 0700
Social Structure and Development 0344
Theory and Methods 0709
Transportation 0999
Urban and Regional Planning 0453
Women's Studies 0453

THE SCIENCES AND ENGINEERING

BIOLOGICAL SCIENCES

Agriculture 0473
General 0285
Agronomy 0475
Animal Culture and Nutrition 0476
Animal Pathology 0359
Food Science and Technology 0478
Forestry and Wildlife 0479
Plant Culture 0480
Plant Pathology 0817
Plant Physiology 0777
Range Management 0746
Wood Technology 0306
Biology 0287
General 0308
Anatomy 0309
Biostatistics 0379
Botany 0329
Cell 0353
Ecology 0369
Entomology 0793
Genetics 0410
Limnology 0307
Microbiology 0317
Molecular 0416
Neuroscience 0433
Oceanography 0821
Physiology 0778
Radiation 0472
Veterinary Science 0786
Zoology 0760
Biophysics 0786
General 0760
Medical 0760

EARTH SCIENCES

Biogeochemistry 0425
Geochemistry 0996

Geodesy 0370
Geology 0372
Geophysics 0373
Hydrology 0388
Mineralogy 0411
Paleobotany 0345
Paleoecology 0426
Paleontology 0418
Paleozoology 0985
Palynology 0427
Physical Geography 0368
Physical Oceanography 0415

HEALTH AND ENVIRONMENTAL SCIENCES

Environmental Sciences 0768
Health Sciences 0566
General 0300
Audiology 0992
Chemotherapy 0567
Dentistry 0350
Education 0769
Hospital Management 0758
Human Development 0982
Immunology 0564
Medicine and Surgery 0347
Mental Health 0569
Nursing 0570
Nutrition 0380
Obstetrics and Gynecology 0354
Occupational Health and Therapy 0381
Ophthalmology 0571
Pathology 0419
Pharmacology 0572
Pharmacy 0382
Physical Therapy 0573
Public Health 0574
Radiology 0575
Recreation 0575

Speech Pathology 0460
Toxicology 0383
Home Economics 0386

PHYSICAL SCIENCES

Pure Sciences 0485
Chemistry 0749
General 0486
Agricultural 0487
Analytical 0488
Biochemistry 0738
Inorganic 0490
Nuclear 0491
Organic 0494
Pharmaceutical 0495
Physical 0754
Polymer 0405
Radiation 0605
Mathematics 0986
Physics 0606
General 0608
Acoustics 0748
Astronomy and Astrophysics 0607
Atmospheric Science 0798
Atomic 0759
Electronics and Electricity 0609
Elementary Particles and High Energy 0610
Fluid and Plasma 0752
Molecular 0756
Nuclear 0611
Optics 0463
Radiation 0346
Solid State 0984
Statistics 0984

Applied Sciences

Applied Mechanics 0346
Computer Science 0984

Engineering 0537
General 0538
Aerospace 0539
Agricultural 0540
Automotive 0541
Biomedical 0542
Chemical 0543
Civil 0544
Electronics and Electrical 0348
Heat and Thermodynamics 0545
Hydraulic 0546
Industrial 0547
Marine 0794
Materials Science 0548
Mechanical 0743
Metallurgy 0551
Mining 0552
Nuclear 0549
Packaging 0765
Petroleum 0554
Sanitary and Municipal 0790
System Science 0428
Geotechnology 0796
Operations Research 0795
Plastics Technology 0994
Textile Technology 0994

PSYCHOLOGY

General 0621
Behavioral 0384
Clinical 0622
Developmental 0620
Experimental 0623
Industrial 0624
Personality 0625
Physiological 0989
Psychobiology 0349
Psychometrics 0632
Social 0451

Carleton University
Ottawa, Canada K1S 5J7

1942-1992

Thesis contains black & white
illustrations which when microfilmed
may lose their significance. The
hardcopy of the thesis is available
upon request from Carleton
University Library.

The undersigned hereby recommend to the
Faculty of Graduate Studies and Research
acceptance of the thesis titled:

**DEVELOPMENT OF OPTIMAL STRATEGIES
FOR
BRIDGE MANAGEMENT SYSTEMS**

submitted by

Hosny Abbas Hosny Mohamed

in partial fulfilment of the requirements for the degree of

Doctor of Philosophy in Engineering

J.L. Humar

Chairman, Department of Civil and Environmental Engineering

A.O. Abd El Halim
Thesis Co-Supervisor

A.G. Razaqpur
Thesis Co-Supervisor

R.C.G. Haas
External Examiner

Faculty of Engineering
Carleton University
May, 1995

To My Parents,

To My Wife,

To My Sisters and

To My Daughter Ameena

ABSTRACT

This study was undertaken to develop a comprehensive framework for a Bridge Management System. The main goal of the system is to integrate all bridge activities in such a way that it optimally utilizes the available resources and minimizes the loss of benefits gained from the road network. The developed system integrated existing procedures, adopted certain principles from pavement management and established new modules. The system incorporates nine main modules, which were delineated by identifying their functions and the interaction among them. System analysis techniques were applied to the developed framework in order to prepare the system for implementation. The functions of all system components were modeled by a set of levelled data flow diagrams presented in a top-down fashion. A database scheme was developed for the BMS and all the data requirements were identified.

Currently used priority setting schemes do not have the ability to optimize the system benefits in order to get optimal solutions. Hence, a network optimization model was developed which can allocate limited funds to bridge projects and which can determine the optimum timing for implementation. Bridge activities were divided into two main groups: rehabilitation and replacement projects, and maintenance activities. Two optimization models were developed to handle these two groups of activities. The dynamic programming approach was utilized to formulate the two models which together constitute a bridge network optimization model. The developed models were tested and proved to be superior to the existing methods.

The rehabilitation and replacement optimization model consists of two combined models; the Outer Model and the Inner Model. The Outer Model was formulated using the dynamic programming technique to perform multi-period optimization. The Inner Model was formulated using two techniques; the dynamic programming technique and the neural networks technique. A comparison between the two techniques revealed the superiority of the dynamic programming technique, accordingly it was used in conjunction with the dynamic programming Outer Model.

ACKNOWLEDGEMENTS

I owe thanks to my supervisors; Professor A.O. Abd El Halim and Professor A.G. Razaqpur, for their constant guidance, immense support and encouragement during every phase of my research.

I gratefully acknowledge the financial assistance provided by the Natural Sciences and Engineering Research Council of Canada, the Transportation Association of Canada and Carleton University.

I wish to acknowledge all members of my Ph.D. advisory committee for their invaluable comments. Special thanks to Professor R. Hafez (Department of Systems and Computer Engineering at Carleton University) for his assistance regarding the Neural Networks technique. I wish to thank Professor F. Farid (North Carolina State University) for the bridge data which he has provided.

I would like to thank Mr. R. Reel and Mr. D. Conte (Ontario Ministry of Transportation) and Mr. A. Wadson (Regional Municipality of Ottawa-Carleton) for helping me get access to their bridge data. I also wish to thank the following persons for their assistance in providing me with reports and information about their bridge management practices: Mr. D. O'Connor and Mr. D. Densmore (U.S. Federal Highway Administration), Mr. J. Lee (North Carolina DOT), Mr. H. Koretzky (Pennsylvania DOT), Mr. R. Woods (Indiana DOT), Mr. W. Winkler (New York DOT) and Mr. I. Friedland (U.S. Transportation Research Board).

I wish to acknowledge my colleagues at the Department of Civil and Environmental Engineering who helped and extended moral support during this work. I would especially like to thank Mr. Hassan, Mr. Abdel Nabi, Mr. Zahw, Mr. Shalaby and Mr. El-Herrawi.

I express my sincerest appreciation and thanks to my wife for her help, support, encouragement and love. I wish to thank her for all what she has sacrificed which make it possible to complete this study. I express my deepest gratitude and thanks to my parents for their continued support and never faltering encouragement, not only during my Ph.D. studies but also through out my whole life.

TABLE OF CONTENTS

ABSTRACT	iv
ACKNOWLEDGEMENTS	v
TABLE OF CONTENTS	vi
LIST OF TABLES	ix
LIST OF FIGURES	xi
INTRODUCTION	1
1.1 Background	1
1.2 Thesis Organization	3
1.3 Problem Definition and Research Needs	5
1.4 Research Objectives and Scope	8
STATE OF THE ART OF BRIDGE MANAGEMENT SYSTEMS	10
2.1 Background	10
2.2 BMS Questionnaire Survey	12
2.3 Review of "Pontis" System	15
2.3.1 "Pontis" Network Optimization Module	15
2.3.2 Drawbacks of "Pontis"	16
2.4 Priority Setting Schemes	17
2.4.1 Sufficiency and Condition Rating	18
2.4.1.1 The FHWA Sufficiency Rating System	18
2.4.1.2 Ontario Condition Rating System	19
2.4.2 Level of Service Deficiency Ranking	21
2.4.2.1 North Carolina's Priority Ranking System	21
2.4.2.2 Pennsylvania's Priority Ranking System	25
2.4.2.3 Comparison of L.O.S. Priority Ranking Formulas	29
2.4.3 Incremental Benefit/Cost Analysis	31
2.4.4 Mathematical Programming Techniques	33
2.4.4.1 Indiana's Model	33
2.4.4.2 North Carolina's Model	37
2.5 Overview of Priority Setting Schemes	38
2.6 Summary	40
A COMPREHENSIVE FRAMEWORK FOR BRIDGE MANAGEMENT SYSTEMS	41
3.1 Introduction	41
3.2 Database Module	42

3.3 Prediction Module	44
3.4 Levels-of-Service Module	46
3.5 R&R Expert Module	46
3.6 Alternative Analysis Module	47
3.7 R&R Network Optimization Module	57
3.8 Maintenance Expert Module	59
3.9 Maintenance Optimization Module	61
3.10 Monitoring and Updating Module	62
3.11 Summary	63
 DEVELOPMENT OF A NETWORK OPTIMIZATION MODEL FOR REHABILITATION AND REPLACEMENT PROJECTS	65
4.1 Introduction	65
4.2 Model Formulation	66
4.2.1 The Outer Model	67
4.2.2 The Inner Model	70
4.3 Demonstration for the Outer Model	71
4.4 Demonstration for The Inner Model	75
4.5 Comparison of Incremental B/C Technique and D.P. Model	80
4.5.1 Incremental B/C Technique	80
4.5.2 Comparison using a Hypothetical Network	81
4.5.3 Comparison Using 25 In-Service Bridges in North Carolina	85
4.6 Importance of the Outer Model	95
4.7 Application of the Outer Model	96
4.8 Summary	99
 UTILIZATION OF NEURAL NETWORKS IN THE NETWORK OPTIMIZATION MODEL	101
5.1 Background	101
5.2 Developed Neural Network	104
5.2.1 Preliminary Formulation	106
5.2.2 The Final Network	112
5.3 Application of the Developed Networks	114
5.3.1 Preliminary Developed Network	116
5.3.2 The Final Network	119
5.3.3 Modification to the Developed Network	121
5.3.4 Parameters of the Final Network	123
5.4 Comparison of D.P. and A.N.N.	126
5.5 Summary	128
 DEVELOPMENT OF A MAINTENANCE OPTIMIZATION MODULE	130
6.1 Introduction	130
6.2 Influence of R&R Schedule on Maintenance Planning	132
6.2.1 Suspension Sub-Module	132

6.3 Priority Factor for Maintenance Activities	134
6.4 The Optimization Model	136
6.4.1 Mathematical Formulation	138
6.5 Application of the Optimization Model	141
6.6 Summary	146
THE DATABASE MODULE	147
7.1 Introduction	147
7.2 The Entity-Relationship Model	147
7.3 The Relational Data Model	149
SUMMARY, CONCLUSIONS AND RECOMMENDATIONS	156
8.1 Introduction	156
8.2 Summary	156
8.2.1 The R&R Network Optimization Module	158
8.2.2 The Maintenance Optimization Module	159
8.2.3 Data Modelling	159
8.3 Conclusions	160
8.4 Recommendations	161
REFERENCES	163
APPENDIX I	169
APPENDIX II	173
APPENDIX III	194
APPENDIX IV	199
APPENDIX V	217
APPENDIX VI	228
APPENDIX VII	236

LIST OF TABLES

Table 2.1	Development Cost of Bridge Management System	14
Table 2.2	Bridge Management Methods in Need of Research	14
Table 2.3	North Carolina Load Capacity Goals	23
Table 2.4	North Carolina Clear Deck Width Goals (2-lane routes)	23
Table 2.5	North Carolina Clear Deck Width Goals (More than 2-lanes)	24
Table 2.6	North Carolina Vertical Clearance Goals	24
Table 2.7	North Carolina Priority Ranking Formula Need Functions	26
Table 2.8	FHWA Bridge Condition Rating System	28
Table 2.9	Functional Classification Factors	30
Table 2.10	Development of TDR for Bridges	30
Table 2.11	State Weighting Factors	32
Table 4.1	Data for Example (1)	76
Table 4.2	Stage (I) of Example (1)	77
Table 4.3	Stage (II) of Example (1)	78
Table 4.4	Stage (III) of Example (1)	79
Table 4.5	Stage (IV) of Example (1)	79
Table 4.6	Data for the Four Hypothetical Bridges	82
Table 4.7	Steps 1,2 & 3 of the Incremental B/C Calculations	83
Table 4.8	Step 4 of the Incremental B/C Calculations	83
Table 4.9	Results of the Two Techniques for Budgets of \$22,000-\$24,0000	84
Table 4.10	Results of the Two Techniques for a Budget of \$25,000	84

Table 4.11	Costs and Benefits for All Bridge Improvement Alternatives in \$1,000 . .	87
Table 4.12	Results of INCBEN	90
Table 4.13	Results of the D.P. Model	90
Table 4.14	Alternatives Selected by INCBEN	92
Table 4.15	Alternatives Selected by the D.P. Model	93
Table 4.16	Results of the Outer Model Application (Group 1)	97
Table 4.17	Results of the Outer Model Application (Group 2)	97
Table 5.1	Data for Example (1)	117
Table 5.2	Data for Example (2)	117
Table 5.3	Values of (q) for Different Sizes of Bridge Networks	125
Table 5.4	The optimal solution for a Budget of \$8 Million	127
Table 6.1	Maintenance Deficiency Points Assignment	135
Table 6.2	Data for a Hypothetical Maintenance Agency	142
Table 6.3	Results of the Ranking Method	143
Table 6.4	Results of the Developed Model	143
Table 6.5	The Activities Selected by the Two Methods	144

LIST OF FIGURES

Figure 1.1	Major Phases and Components of the Systems Method	2
Figure 1.2	The Hierarchy of Planning Levels	4
Figure 2.1	Material Condition Rating of Structure Components	20
Figure 2.2	Performance Condition Rating of Structure Components	20
Figure 2.3	Load Capacity Need Functions	32
Figure 2.4	Area of Performance Curve Obtained by Rehabilitation	35
Figure 3.1	The Developed Bridge Management System Framework	43
Figure 3.2	Members of the Expert System Building Process	48
Figure 3.3	Quantification of Travel Time Costs	52
Figure 3.4	Cost Profiles for Alternative (A)	54
Figure 3.5	Cost Profiles for Alternative (E)	55
Figure 3.6	Development of the Input File	58
Figure 3.7	The Maintenance Expert Module	60
Figure 4.1	Demonstration for the Network Optimization Model	72
Figure 4.2	Demonstration for the Network Optimization Model	73
Figure 4.3	Demonstration for the Network Optimization Model	74
Figure 4.4	Comparison of the Net Benefits Gained by INCBEN and Sufficiency Rating	86
Figure 4.5	Comparison of the Net Benefits Gained by INCBEN and D.P. Model	94
Figure 5.1	Human Neural Circuits	103
Figure 5.2	Structure of a Single Processing Element	103

Figure 5.3 Architecture of the Preliminary Network	107
Figure 5.4 Functions Used to Enforce the Zero/One Property	110
Figure 5.5 Architecture of the Final Network	115
Figure 5.6 Objective Function Behaviour During Iteration in Example (1)	118
Figure 5.7 Objective Function Behaviour During Iteration in Example (2)	118
Figure 5.8 Convergent Patterns of Objective Function (Z) in Example (3)	120
Figure 5.9 Convergent Patterns of Penalty Function (g(x)) in Example (3)	120
Figure 5.10 Convergent Patterns of Penalty Function (g(x)) in Example (4)	122
Figure 5.11 Convergent Patterns of Objective Function (Z) in Example (4)	122
Figure 5.12 Convergent Patterns of Objective Function (Z) in Example (5)	124
Figure 5.13 Convergent Patterns of Penalty Function (g(x)) in Example (5)	124
Figure 6.1 Components of the Maintenance Optimization Module	137
Figure 6.2 Steps of Preparing the Maintenance Activity List	139
Figure 6.3 Comparison of the Ranking Method with the Developed Model	145
Figure 7.1 The Entity-Relationship Diagram	148

CHAPTER 1

INTRODUCTION

1.1 Background

Fixed facilities such as bridges and pavements represent the major investment in a highway network. Unfortunately they do not last forever and are in constant need of maintenance, rehabilitation and replacement (MR&R). The main problem faced by most transportation agencies is that the cost of meeting this need is more than the available budgeted funds. Bridge Management System may be considered a new approach that has been adapted from the successful application of the system concepts to pavement management. However, pavement management systems are still in need for further research. Haas et al. (1994), founders of the pavement management systems, have defined the systems methodology as "a body of knowledge that has been developed for the efficient planning, design, and implementation of new systems and for structuring the state of knowledge on an existing system or modelling its operation". Figure 1 represents the major phases and components of the systems method which is a logical presentation of all activities taking part in solving the problem.

A Bridge Management System (BMS) provides an approach to organizing and carrying out the MR&R activities in order to meet the network needs, using the available funds in the most effective way. Defining the term "Needs" for a bridge network is a very important task. At the network level "Needs" can be defined as the group of improvement alternatives which would minimize the losses of the network benefits. At the project level "Needs" can be viewed as the least-cost improvement alternative required to achieve particular levels of service goals. Thus it is important for the responsible agency to clearly determine its expected benefits and to establish its desired level of service goals.

Figure 1.1 Major Phases and Components of the Systems Method
(Source: Haas et al., 1994)

Figure 2 shows the hierarchy of planning levels that are involved in a bridge management system. The decision at each level is how to allocate budgets to its sectors in order to maximize the total social benefits. The fourth level represents the bridge management level or the network level. The decision of this level would include the determination of the rehabilitation and replacement projects needed for the bridge network. It also would assign priorities to these projects so that they can be scheduled within the analysis period and under a limited budget. The project level is the last one and it concerns the details of each project and how to choose the least-cost action required to eliminate levels-of-service deficiencies.

The primary objective of a Bridge Management System is to integrate all the activities related to the management of a network of bridges in a comprehensive computerized system which can address the network needs using the available resources in the most efficient and cost-effective manner. A BMS assists decision-makers to avoid conflict between short-term decisions and long-term trends. FHWA (1989) stated "A long term objective of bridge management is to eliminate the present backlog of needs and to maintain a state in which expenditures for bridge improvements each year match the needs that accrue each year".

1.2 Thesis Organization

The thesis consists of eight chapters. The remainder of Chapter 1 includes a definition of the specific problem to be addressed in this research as well as the research objectives and scope.

Chapter 2 provides a state-of-the-art review for Bridge Management Systems.

Chapter 3 describes a comprehensive framework that has been developed for Bridge Management Systems.

Figure 1.2 The Hierarchy of Planning Levels
(Source: Haas et al., 1994)

Chapter 4 includes the details of a network optimization model that has been developed to allocate limited funds to bridge rehabilitation and replacement projects. The model formulation is presented as well as its application.

Chapter 5 shows how Neural Networks can be utilized in BMS. The chapter presents the formulation of a Neural Network that could be used in the network optimization model described in Chapter 4. The limitations of this technique are also identified.

Chapter 6 presents an optimization module that allocates the transportation agencies limited resources of labour and equipments to bridge maintenance activities. The influence of rehabilitation and replacement decisions on maintenance planning has been integrated in the developed module.

Chapter 7 presents the database module. Two data models are used to present the data of the system; the Entity-Relationship model and the Relational data model.

Chapter 8 contains the conclusions and some recommendations.

1.3 Problem Definition and Research Needs

The first attentions to BMS were drawn by the Silver Bridge collapse in west Virginia which killed 46 people in 1969. Two other failures occurred; the hinged Connecticut Turnpike bridge over the Mianus river in 1983 and the bridge pier failure on Interstate 90 in New York state in 1987.

The main problem faced by most transportation agencies is that the cost of maintenance, rehabilitation and replacement (MR&R) of bridges is more than the available budgeted funds. Deferred maintenance practice and low prioritization of budget dollars

allocated to bridge repair projects only exacerbates this situation. About one-half of the 574,000 highway bridges in the U.S.A. were built before 1940 (NCHRP, 1987). In 1986, the Federal Highway Administration (FHWA) reported that 42 percent of these bridges were classified as structurally deficient or functionally obsolete. A bridge is classified structurally deficient if its deterioration has reached the point that the bridge is inadequate to carry some types of vehicles, i.e. it is unsafe to be used. Functional obsolescence means that bridge configurations become inadequate to serve all types of traffic. This may happen due to insufficient width, insufficient vertical clearance, or poor alignment with the approach roadway. The cost of rehabilitation of those deficient bridges would be approximately \$50 billion. This picture was the "alarm-bell" for many states to start developing bridge management systems.

Much of bridge engineering research in Canada has been addressed to bridge design code, in particular to the Ontario highway bridge design code. The bridge analysis, live loads, soil-steel structures and timber bridges have been widely investigated (Bakht and Jaeger, 1988). In Canada, presently the problem is not as serious as in the U.S.A. because Canadian bridges are relatively new compared to bridges in the U.S.A, but it is a problem which will need to be confronted in the near future.

The Ontario provincial highway system comprises 22,000 kilometres of highway and approximately 3,000 bridges. The bridges comprise less than 1 percent of the system's size yet nearly 10 percent of its value. The investment in this network is estimated at around \$30 billion. The cost of operations and general maintenance activities totalled almost \$300 million in fiscal 1990/91. The provincial auditor concluded in his 1992 annual report (Ontario Government, 1992) that the level of preventive maintenance performed by the MTO is less than satisfactory. Inspections revealed that over 1,300 bridges had not received adequate maintenance. The auditor wrote, "Current maintenance planning and the allocation of funds to the various districts is not driven by identified needs". Deferred maintenance practice and low prioritization of budget dollars can accelerate deterioration and increase bridge rehabilitation cost. For instance, bridge rehabilitation spending rose by more than 60

percent between 1987 and 1991, (Ontario Government, 1992). The provincial auditor recommended that identified needs and physical condition surveys be used to develop a detailed preventive maintenance schedule.

Buckle (1988) summarized the research needs in bridge management systems (BMS) and divided them into two major categories: the first one is the BMS programming and the second is strategic long term planning. The former includes optimization models which are used in the prioritization and selection procedures. The later comprises the development of accurate models to predict the future needs.

Relatively little research work has been done in the area of bridge management. But recently the development of bridge management systems has been emphasised because of the imbalance between the needs of bridge networks and the available resources. The main problem is that there are too many deficient bridges but the available budget is not sufficient to eliminate these deficiencies. To address this problem, the following research needs have been specified:

- 1) There is no available comprehensive system which integrates all bridge activities in a way that would avoid any conflict between short term decisions and long term trends. Engineering expertise should be integrated in the management process. Framing such a system is the first step in solving the bridge problem.
- 2) Priority Setting Schemes currently used to allocate funds to bridge projects do not utilize the available resources in the most efficient and cost-effective manner. Network optimization models need to be developed in order to minimize loss of system benefits.
- 3) Lack of coordination between bridge rehabilitation and replacement programs and maintenance planning results in wasting the limited resources in redundant activities.
- 4) A Bridge Management System incorporates a large amount of data with different types and structures. All data items required for a BMS need to be clearly identified, an appropriate database scheme should be designed.

These research needs represent the core of the research carried out and presented in this thesis.

1.4 Research Objectives and Scope

The main objective of a bridge management system is to meet the bridge network needs using the available resources in the most effective way. In reviewing the literature it has been shown that low prioritization of budget dollars allocated to bridge activities has led to imbalance between the needs of a bridge network and the available resources. The lack of a comprehensive system which integrates all bridge activities in a logical way has exacerbated the situation.

The issues discussed earlier lead to the main goal of this research which is to develop a BMS and to investigate potential strategies to provide optimal allocation of resources to bridge activities. These strategies will assist decision-makers to achieve level of service goals and eliminate the present backlog of needs. In order to achieve the main goal of this research a number of objectives need to be achieved and these are discussed below.

The first objective is to design a framework for BMS and to identify its main modules. This framework will integrate all bridge related activities in a comprehensive system. The function of each module and its input and output will be delineated. Interaction among BMS modules will be clearly identified.

The second objective is to develop a priority setting scheme which optimizes the system benefits to allocate the available budget to bridge replacement and rehabilitation projects, and which determines the best timing for carrying out these projects. This task includes the formulation of a network optimization model for the bridge replacement and rehabilitation activities. The dynamic programming approach will be utilized to formulate the network model. A sub-model will be developed using two approaches. The first one will use the dynamic programming technique to be formulated; Artificial Neural Networks (A.N.N.) will be used in the second approach to solve the sub-model. The objective of using A.N.N. is to overcome the calculation time and the memory storage space required by the

first approach. However, the applicability of Neural Networks will be investigated and the best technique will be selected.

The third objective is to integrate bridge maintenance activities into the BMS and to consider the influence of rehabilitation and replacement programs on maintenance planning. To achieve this objective, a maintenance optimization module will be developed.

The fourth and final objective is to develop an appropriate database scheme which can provide an effective and efficient way of handling data. Proper knowledge of the BMS components and a proper understanding of the optimization process will help to define the data requirements and the way data need to be organized. An Entity-Relationship model will be developed as well as a relational data model.

The BMS framework developed in this thesis includes some artificial intelligence systems. The functions of these systems were identified but due to limited time and resources, the complete development is beyond the scope of this study. Finally, for the verification of some of the developed models in this thesis, hypothetical data were used due to lack of actual data from real structures.

CHAPTER 2

STATE OF THE ART OF BRIDGE MANAGEMENT SYSTEMS

2.1 Background

Recent efforts in developing BMS do not mean that management was not applied to bridge-related activities in the past. Today the number of bridges, their age differential and their needs have grown so large that traditional management practices have become inadequate for the current situations. In the early 1970s, bridge management started in the form of establishing databases for bridges. The U.S. National Bridge Inventory (NBI) is one of the few comprehensive databases available for bridges. The United States Federal Highway Administration (FHWA) depends on the NBI to determine eligibility of projects for federal funding using a sufficiency rating criterion. The U.S. National Bridge Inspection Standards (NBIS) requires that each bridge be inspected every two years with 116 data items to be recorded (FHWA, 1988). These items include data describing the bridge location, age, geometric, material and structural type. It also contains information about the bridge condition and proposed improvements. Appendix I provides a list of those data items.

Individual states in the U.S. have begun to develop their own databases to meet the FHWA requirements. The Pennsylvania Department of Transportation began implementing its Structure Inventory Record System (SIR) in 1982. For a given bridge, the SIR may contain up to 210 data items including the 116 items of the NBIS. The SIR stores data for about 54,000 bridges (PennDOT, 1987). The Texas Department of Transportation maintains about 140 items of information for its 47,000 structures in its database which is called BRINSAP (Weissmann et. al., 1991). In Ontario, the Ontario Structure Inventory System

(OSIS) contains data about the 3,000 bridges under the MTO jurisdiction (MTO, 1981). Because of the inadequacy of existing bridge management procedures in reducing the total number of deficient bridges, many states have recognized the need for an efficient Bridge Management System to ensure the most cost-effective use of the available resources. North Carolina and Pennsylvania are the leaders in establishing bridge management concepts and procedures. Many of the other states and provinces in U.S.A. and Canada are expected to adopt or modify systems developed by others. Recognizing that a bridge management system was a high priority of many states, in 1985 the National Cooperative Highway Research Program (NCHRP) in the U.S.A. initiated a research project for the development of bridge management systems with a total fund of \$495,000. The objective of this research was to develop a comprehensive system for managing a network of bridges. The NCHRP Report 300 (Hudson et. al., 1987) contains the result of the first phase of research, which provides a conceptual framework for a Bridge Management System. The second phase was initiated in 1987 to finalize the concepts and procedures required for the BMS and to produce a PC-based computer software package. The resulting software was tested by several state and local transportation agencies, but a large number of errors and some major deficiencies were found (NCHRP, 1991).

Another research project was started in 1992 with an NCHRP fund of \$35,000. The objective of this project is to develop, validate and document a fully operational microcomputer-based BMS software package. The responsibility of developing this software package was given to the NET Corporation, Ontario, Canada. Lipkus (1993) stated that the models and analysis procedures to be used will be based on state-of-the-art conventional practices. This project was scheduled for completion in July, 1994, but it has been delayed. AASHTO intends to distribute this BMS software to interested states for testing and evaluation. There is not much information yet about this project, but Lipkus (1993) stated that incremental benefit/cost technique will be used for the network optimization analysis. As will be discussed later, this technique can not provide the optimal scheduling for bridge projects. The FHWA under its Demonstration Project 71 has sponsored the development of another BMS software package. This software, called "Pontis", was developed by

Cambridge Systematics Inc. and Optima Inc., was completed in January 1992, and is now going to be adopted by the AASHTO software support program (Thompson et. al., 1993). Pontis is now being tested by many transportation agencies and implemented by more than ten states. After being evaluated by the Ministry of Transportation of Ontario (MTO) at the Bridge Management Section, Pontis was not recommended for adaptation in Ontario. Because the adoption would cost the MTO about \$228,000, while in-house development would cost much less (Conte et. al. 1993).

In recognition of the value and importance of BMS, the Intermodal Surface Transportation Efficiency Act (ISTEA) in the U.S.A. required that each state should have a running BMS by October, 1998. In May 1993, a questionnaire survey was conducted by the New York State Department of Transportation to ascertain the progress of various states in developing a Bridge Management System. The results of this survey will be presented in the following section. Since "Pontis" is intended to be adopted by many states, it will be reviewed in Section 2.3. After reviewing Bridge Management Systems on a comprehensive basis, represented by "Pontis", priority setting schemes for bridge rehabilitation and replacement projects will be reviewed. This scheme represents the core of the BMS and it performs the main function required by a BMS. Priority setting schemes include a wide spectrum of techniques ranging from ranking on subjective basis using engineering judgement to very complex optimization models. A review of the literature on these techniques will be presented in Section 2.4.

2.2 BMS Questionnaire Survey

A questionnaire survey was undertaken by the Bridge Management System Unit of the New York State Department of Transportation Structures Division (N.Y. DOT, 1993). The questionnaire objective was to track the progress of BMS development. The replies had been received as of May 1, 1993 from forty seven states and six Canadian provinces. The

Canadian provinces are: Ontario, Alberta, Manitoba, New Brunswick, Newfoundland and Nova Scotia. Adopting a system developed by others was the choice of 71 percent of the respondents. Most of those intend to adopt "Pontis". Few states are actively developing bridge management systems to meet their specific needs. Nova Scotia is the only respondent which has no plans for developing a BMS at this time. The survey indicated that by 1996, 75 percent of the respondents will have a running bridge management system. Responding to a question about who will take the responsibility of the system development, the answers indicated that in-house staff are preferred over consultants. The average number of staff-years estimated for BMS in-house implementation effort was 4.8 years. Table 2.1 shows the estimations of the respondents for the BMS development costs, excluding data collection and implementation. The average cost calculated from the Table was \$542,000. From the survey results it was concluded (N.Y. DOT, 1993) that the cost of adopting the "Pontis" system would be as little as a few thousand dollars, while the MTO reported that this adoption would cost them about \$228,000 (Conte et. al. 1993).

Table 2.2 illustrates the answers to question 12 of the survey which was: "BMS requires expansion of existing methods/procedures. Please identify areas where your BMS development effort will be seeking improved methods". One can conclude from Table 2.2 that priority setting schemes and the project selection optimization procedures are in need of more research and effort. The bridge condition forecasting and the estimation of its remaining life are also of high importance. Improved cost estimation methods are also required. Seventy three percent of the states and provinces responded that they expect to save money by using a Bridge Management System. Fourteen percent gave no choice, while the remaining 13 percent did not expect any savings but they did not provide any reasons. The survey provides a good picture of the BMS development efforts being made across the United States and Canada. Most of the states and the provinces have recognized the importance of having a bridge management system. This recognition has been translated to actual efforts in some states. Pennsylvania and North Carolina appear to be the leaders in this field. The FHWA sponsored "Pontis" system has strong support from most of the other states. The survey indicated that BMS methods still need further research and investigation.

Table 2.1 Development Cost of Bridge Management System
(Source: N.Y. DOT, 1993)

Category (\$1000)	Respondents
User Fee	3
0 - 24	1
24 - 50	3
50 - 99	5
100 - 199	3
200 - 299	5
300 - 399	-
400 - 499	3
500 - 999	2
1000 - 1900	1
2000 - 2900	2
> 3000	1

Table 2.2 Bridge Management Methods in Need of Research
(Source: N.Y. DOT, 1993)

Method	Respondents
Optimization of capital & maintenance improvements	42
Forecasting conditions	36
Capital project selection	34
Maintenance project selection	33
Cost estimation methods	26
Project design	4

2.3 Review of "Pontis" System

"Pontis" has been developed, under the FHWA Demonstration Project 71, by Cambridge Systematics Inc. and Optima Inc. The first version was completed in January 1992. Pontis represents state-of-the-art of a complete BMS. The system consists of five main modules; database module, network optimization module, condition states and feasible action module, prediction module and cost module. The first Module is a database management system, which has been coded specially for Pontis. This software can handle a network having up to 50,000 bridges. Each bridge is divided into its constituent elements. For each element, the possible condition states are defined in the second module. This module contains also the feasible actions for each condition state. The third module will be handled in a separate Section because it is the core of the system. The prediction module predicts future bridge conditions using a Markovian approach. The function of the fifth module is to estimate activity costs and user costs.

2.3.1 "Pontis" Network Optimization Module

The function of this module is to allocate the available budget to bridge projects. The main feature of this module is that it has divided bridge projects into two groups. Each group will be handled by a separate sub-module, then a third sub-module will combine their output. The first group has been named "Maintenance, Repair and Rehabilitation Actions", while the second group is the "Improvement Actions". The first group includes such actions that improve the condition of the bridge which may deteriorate again with time. This will not include changing the original design of the structure. The second group of actions includes the improvement actions recommended due to deficiencies in level-of-service goals. This may include changing the original design of the structure.

The objective of the Maintenance, Repair and Rehabilitation Optimization Sub-Module

is to minimize the annual expenditure by the agency. For each element of the bridge, using a Linear Programming approach, the least cost action will be chosen. The actions and their costs will be combined for each bridge. The last step is to rank bridge projects using their incremental benefit/cost ratios. The Improvements Optimization Sub-Module sets its objective to maximize the user cost savings. The recommended actions will be ranked using their incremental benefit/cost ratios. The third sub-module is called "Integration and Program Planning". The function of this sub-module is to integrate the output of the previous sub-modules. The actions recommended for each bridge from the first two sub-modules are added. All bridge projects will be ranked by their incremental benefit/cost ratios and those bridges above the budget limit will be carried out. The rest of the list will be analyzed again using their predicted conditions. This procedure will be repeated for the required analysis period.

2.3.2 Drawbacks of "Pontis"

"Pontis" has the advantage of being the first complete software developed for Bridge Management Systems. It has gathered the results of some of the previous efforts invested in BMS and it provides a single handy tool. However, some drawbacks of its procedures have been identified, and they are:

- 1) "Pontis" network optimization module combines two incompatible sets of actions while it differentiates between two sets of actions within the same class. It combines maintenance activities with major rehabilitation and replacement projects, while it differentiates among major rehabilitation and replacement projects and improvement projects. The maintenance activities are usually performed by the agency's maintenance crews and have a separate budget. The rehabilitation and replacement projects should be analyzed in conjunction with the improvement projects because both of them have the same effects on the system, on the agency costs and benefits, and on the user costs and benefits. The separation between them leads to ignoring the user costs associated with rehabilitation and replacement projects.

- 2) "Pontis" uses the incremental benefit/cost method to rank the recommended bridge projects. This method, as will be shown in Chapter 4, does not generate the optimal decision for allocating limited funds.
- 3) Dividing a roadway into sections to choose the best action for each section may be suitable for pavement management, but dividing a bridge into elements to choose the best action for each one will not result in a good coordinated solution.
- 4) Using a Linear Programming approach to find the best action for each bridge element may work for each individual element, but will not result in optimizing the overall network benefits.

2.4 Priority Setting Schemes

Priority setting schemes for bridge rehabilitation and replacement projects represent the core of the BMS. The New York DOT's survey indicated that it is the part of the BMS that needs further research and investigation. In the past, ranking on subjective basis using engineering judgement was acceptable for young and small networks of bridges. For such large and old networks as those in North America, optimization principles should be applied in allocating budget to bridge projects.

The cost of rehabilitation and replacement (R&R) of bridges consumes most of the funding available for bridge improvements. Therefore, the budget required for those activities should be carefully allocated. Setting priorities for R&R activities is a typical multi-attribute decision-making problem which requires simultaneous evaluation of several related factors. The bridge rehabilitation and replacement project ranking procedures currently available can be grouped into four types: sufficiency rating, level-of-service deficiency ranking, incremental benefit/cost analysis and mathematical programming. The four types are discussed in the following Sections.

2.4.1 Sufficiency and Condition Rating

2.4.1.1 The FHWA Sufficiency Rating System

The sufficiency rating (SR) approach has been developed by The FHWA for determining eligibility for bridge replacement or rehabilitation funds under the Highway Bridge Replacement and Rehabilitation Program. Deficiency points are subtracted from 100 to calculate a bridge's SR. Thus, when SR is equal to 100 this represents an entirely sufficient bridge, with SR being given by the following formula (FHWA, 1988):

$$SR = S_1 + S_2 + S_3 - S_4 \quad (2.1)$$

Where:

S_1 = function of Structural Adequacy and Safety;

S_2 = function of Serviceability and Functional Obsolescence;

S_3 = function of Essentiality for Public Use; and

S_4 = Special Reductions.

Structural Adequacy and Safety:

$$S_1 = 55 - (a + b) \quad (2.2)$$

Where:

S_1 = a maximum of 55% and shall not be less than 0%;

a = a parameter which reflects the lowest rating of superstructure and substructure and it can be determined from a table in FHWA (1988); and

b = a parameter which reflects the reduction of load capacity and it can be estimated from a chart available in FHWA (1998).

Serviceability and Functional Obsolescence:

$$S_2 = 30 - (C_1 + C_2 + \dots + C_{13}) \quad (2.3)$$

Where:

S_2 = a maximum of 30% and shall not be less than 0%;

C_s = parameters representing thirteen items and they are: lanes, average daily traffic (ADT), approach roadway width, structural type, bridge width, over-clearance, under-clearance, deck condition, structural evaluation, deck geometry, waterway adequacy,

approach roadway alignment and defense highway designation.

Essentiality for Public Use:

$$S_3 = 15 - (d + f) \quad (2.4)$$

Where:

S_3 = a maximum of 15% and shall not be less than 0%;

d = 2% if the bridge was on a defense route and 0% otherwise; and

f = $0.006375 (\text{ADT} \times \text{Detour}) / (S_1 + S_2)$.

Special Reductions:

These reductions can be due to detour length, ADT or defense highway designation and shall not exceed 13% and shall not be used if $(S_1 + S_2 + S_3)$ less than 50%.

2.4.1.2 Ontario Condition Rating System

This system represents another form of the condition rating systems and was developed by the Ministry of Transportation of Ontario (MTO, 1991). Two condition ratings were defined and they are the material condition rating (MCR) and the performance condition rating (PCR). The system categorized the structure components into three groups: primary, secondary and auxiliary. The material condition rating ranges from 1 to 6 and will be assigned to each component to represent the observed defects in the materials. The number 1 represents very severe condition, while number 6 represents virgin condition. Description of each rating level is described in the Ontario Structure Inspection Manual (OSIM), MTO (1991). Figure 2.1 gives guidelines for the application of the MCR based on the percentage loss of component cross-section, surface area or length affected.

The performance condition rating represents the condition of the component based upon its ability to perform its intended function in the structure. The same numerical system used for the MCR is used for the PCR. "Performance defects may be related to material defects, due to errors in design or construction, as a result of unexpected behaviour of the

Figure 2.1 Material Condition Rating of Structure Components

(source: Ministry of Transportation of Ontario, 1991)

RATING	PERFORMANCE CONDITION OF COMPONENT	APPROXIMATE PERCENTAGE REDUCTION IN THE CAPACITY OF THE COMPONENT TO PERFORM ITS INTENDED FUNCTION IN THE STRUCTURE		
		PRIMARY COMPONENTS	SECONDARY COMPONENTS	AUXILIARY COMPONENTS
6	VERY GOOD	0	0	0
5	GOOD	0 TO 5%	0 TO 10%	0 TO 20%
4	FAIR	5 TO 10%	10 TO 20%	20 TO 40%
3	POOR	10 TO 15%	20 TO 30%	40 TO 60%
2	URGENT	15 TO 20%	30 TO 40%	60 TO 80%
1	CRITICAL	OVER 20%	OVER 40%	OVER 80%

Figure 2.2 Performance Condition Rating of Structure Components

(source: Ministry of Transportation of Ontario, 1991)

structure, or due to defects in other components" (Manning and Reel, 1986). Figure 2.2 provides general guidelines for the application of the PCR based on the disability of the component to perform its intended function. The performance condition rating of the structure as a whole (PCRS) will be taken as the lowest performance condition rating of a primary component.

2.4.2 Level of Service Deficiency Ranking

2.4.2.1 North Carolina's Priority Ranking System

In 1983 about 58 percent of North Carolina's bridges were classified as deficient by the sufficiency ratings. Many of these bridges were built with narrow geometry and low load capacities, which produce low SR, despite the fact that they were in good condition. The level-of-service (L.O.S) approach was developed first at North Carolina State university by Johnston and Zia (1983). This approach recognized that priorities should be set according to the degree to which a bridge is deficient in meeting public needs. To evaluate a bridge in meeting its intended function, three quantifiable bridge characteristics were selected: load capacity, clear deck width and vertical roadway underclearance and overclearance. For different traffic volumes and different roadway classifications, level-of-service goals were assigned to each of these bridge characteristics.

Two different goals were established, acceptable and desirable. Johnston and Zia (1983) defined the acceptable goals as "the minimum level which would accommodate essential vehicles such as passenger cars, school buses, fire trucks, residential garbage trucks, heating oil home delivery trucks and two axle electrical utility line trucks on all routes". The "desirable" goals generally are the same as North Carolina bridge policy for new bridge construction. The load capacity goals were established based on a survey conducted by the NCDOT Bridge Maintenance Unit to determine the weights of essential service vehicles. Table 2.3 illustrates these goals with a minimum of 16 tons. Clear bridge deck width goals

were established to minimize accidents related to narrow bridges. Table 2.4 shows width goals for two lane bridges. For bridges with more than two lanes, the width goals are the sum of lane and shoulder dimensions given in Table 2.5, adequate vertical clearance would reduce detours of vehicles serving industry, farms and commerce as well as reducing collision damage. Table 2.6 illustrates the vertical clearance goals with a minimum acceptable of 14.0 feet which is slightly higher than the legal maximum height of 13.5 feet. Many other states have adapted their own L.O.S. goals using similar criterias.

Priority ranking formulas based on L.O.S. deficiency can be expressed by the following general equation (FHWA, 1989):

$$P.I = \sum_n W_n F_n(a,b,...) \quad (2.5)$$

Where:

P.I= priority index used in rating,

W_n = weight assigned to the nth need function,

F_n = nth need function,

a,b,...= the need function values representing the bridge attributes.

The need functions measure the degree to which the level-of-service goals are achieved. Each country or state should establish its own level-of-service goals which reflect its bridge program objectives.

The following formula represents North Carolina's priority ranking system based on its level of service goals (Johnston and Zia, 1983):

$$DP = CP + WP + VP + LP \quad (2.6)$$

Where DP is the total deficiency points on a scale of 0 to 100 with 0 representing no deficiency. CP, WP, VP and LP are need functions for load capacity, clear deck width,

Table 2.3 North Carolina Load Capacity Goals

(Source: Johnston and Zia, 1983)

Road Over Functional Classification	Single Vehicle Capacity	
	Acceptable	Desirable
Interstate and Arterial	33.6 tons	33.6 tons
Major Collector	25 tons	33.6 tons
Minor Collector	16 tons	33.6 tons
Local	16 tons	33.6 tons

Table 2.4 North Carolina Clear Deck Width Goals (2-lane routes)

(Source: Johnston and Zia, 1983)

Road Classification	Current ADT	Clear Width (ft)	
		Acceptable	Desirable
Interstate and Arterial	ADT $\leq$ 800	22	24
	801 - 2000	24	36
	2001 - 4000	26	40
	Over 4000	28	40
Major & Minor Collectors and Local Roads	ADT $\leq$ 800	20	24
	801 - 2000	22	28
	2001 - 4000	24	30
	Over 4000	26	30

Table 2.5 North Carolina Clear Deck Width Goals (More than 2-lanes)

(Source: Johnston and Zia, 1983)

Road Classification	Current ADT	Acceptable		Desirable	
		Lane	Shoulder	Lane	Shoulder
Interstate and Arterial	ADT $\leq$ 800	10	1	12	4
	801 - 2000	10	2	12	6
	2001 - 4000	11	2	12	8
	Over 4000	11	3	12	8
Major & Minor Collectors and Local Roads	ADT $\leq$ 800	9	1	10	2
	801 - 2000	9	2	11	3
	2001 - 4000	10	2	12	3
	Over 4000	10	3	12	3

Table 2.6 North Carolina Vertical Clearance Goals

(Source: Johnston and Zia, 1983)

Road Under Functional Classification	Underclearance (ft)	
	Acceptable	Desirable
Interstate and Arterial	14.0	16.5
Major and Minor Collector	14.0	15.0
Local	14.0	15.0

vertical clearance and remaining life, respectively. The weights assigned to the previous need functions are 70, 12, 12 and 6, respectively. Table 2.7 illustrates the formulas used for calculating individual need functions.

The load capacity deficiency would generate extra user costs due to time lost and detour around a posted bridge. The increases in width deficiency and ADT were assumed to be associated with linear increase in the number of accidents and resulting costs. The magnitude of user costs would increase linearly with vertical clearance deficiencies and ADT. The estimated remaining life priority was included in the deficiency points to provide some weighting for general bridge condition. A significant degree of judgement is involved. A remaining life above 15 years would indicate good overall condition, while 3 years or less means a maximum deficiency of 6 points.

After estimating "DP" for all bridges, the bridges will be ranked in a descending order of their "DP". The bridges at the top of the list will receive fund for their projects and one can go down in the list until the available budget is exhausted. This procedure is to be repeated every year.

2.4.2.2 Pennsylvania's Priority Ranking System

The Commonwealth of Pennsylvania has about 54,000 bridges on the state and local highway systems. In 1987, approximately 30 percent of these bridges were classified as structurally deficient or functionally obsolete. To get these bridges to a minimum acceptable condition would cost about \$4.0 billion. The bridges should be inspected at least every two years, which means that about 60 bridges would be inspected every working day.

There were too many deficient bridges and the available budget was not enough to get them to an acceptable condition. This situation exemplified the need for a Bridge Management System (BMS). In 1984, the Pennsylvania Department of Transportation (PennDOT)

Table 2.7 North Carolina Priority Ranking Formula Need Functions

(Source: FHWA, 1989)

<p>Single Vehicle Load Capacity Priority (CP)</p> $CP = WC \times \left[\frac{CG - SV}{10} \right] \times (0.6KA + 0.4KD)$ <p>where</p> <p>WC = Capacity weighting</p> <p>CG = Capacity goal, tons</p> <p>SV = Single vehicle posting, tons</p> $KA = \frac{(ADTO)0.30}{12}$ $KD = \frac{DL}{20} \times \frac{ADTO}{4000}$ <p>ADTO = Average daily traffic of over route</p> <p>DL = Detour length, miles</p>	<p>Clear Bridge Deck Width Priority (WP)</p> $WP = WW \times \left[\frac{WG - CDW}{3} \right] \times \frac{ADTO}{4000}$ <p>where</p> <p>WW = Width weighting</p> <p>WG = Width goal, feet</p> <p>CDW = Clear deck width of bridge, feet</p> <p>ADTO = Average daily traffic of over route</p> <hr/> <p>Estimated Remaining Life Priority (LP)</p> $LP = WL \times \left[\frac{1 - (RL - 3)}{12} \right]$ <p>where</p> <p>WL = Remaining life, weighting</p> <p>RL = Estimated remaining life, years</p>
<p style="text-align: center;">Vertical Roadway Under/Overclearance Priority (VP)</p> $VPU = WV \times \left[\frac{UG - VCLU}{2} \right] \times \frac{ADTU}{4000} \quad VPO = WV \times \left[\frac{OG - VCLO}{2} \right] \times \frac{ADTO}{4000}$ $VP = VPU + VPO$ <p>where</p> <p>WV = Vertical clearance weighting</p> <p>UG = Underclearance goal, feet</p> <p>VCLU = Existing vertical underclearance, feet</p> <p>ADTU = Average daily traffic of under route</p> <p>OG = Overclearance goal, feet</p> <p>VCLO = Existing vertical overclearance, feet</p> <p>ADTO = Average daily traffic over route</p>	

established a Bridge Management Task Group to confirm the urgent need for BMS and to find out if the effort to develop such a system would be worthwhile and do-able. In their report (PennDOT, 1987), the group agreed that the development of such a system is feasible and that it is a very important tool for better management. After that a work group of ten persons was established and they performed a study which formed the basis for PennDOT BMS.

A total deficiency rating (TDR) is used for the prioritization of bridges for rehabilitation and replacement. Deficiencies are evaluated in three general categories: level-of-service capabilities, bridge condition, and other related characteristics. These deficiencies are to be added together to get a TDR on a scale which ranges from 0 to 100. The determination of TDR is based on parts of the Federal Sufficiency Rating System (FHWA, 1988) and on the system developed by North Carolina State University (Johnston and Zia, 1984).

The level-of-service deficiencies (LOSD) include four characteristics: load capacity deficiency (LCD), clear deck width deficiency (WD), the vertical clearance over the bridge deficiency (VCOD), and the vertical clearance under the bridge deficiency (VCUD). These deficiencies are estimated by comparing the actual load capacity, deck width and vertical clearances with the L.O.S. goals which have been developed for PennDOT. The bridge condition deficiency (BCD) depends on the conditions of the three primary elements: superstructure, substructure and bridge deck. The BCD is calculated as the sum of the conditions deficiencies for the three elements: SPD, SBD and BDD. The bridge condition ratings are calculated by converting the corresponding FHWA bridge ratings, using some coefficients developed by PennDOT, 1987. Table 2.8 describes the FHWA bridge condition rating system. The other related deficiencies (ORD) include three elements and they are: the remaining life deficiency (RLD), the approach roadway alignment deficiency (AAD) and the adequacy of the waterway deficiency (WAD). These deficiencies are calculated using equations developed for PennDOT's BMS.

Table 2.8 FHWA Bridge Condition Rating System

(Source: PennDOT, 1987)

Condition Rating	Description
N	Not applicable
9	New condition
8	Good condition - no repairs needed
7	Generally good condition - potential exists for minor maintenance
6	Fair condition - potential exists for major maintenance
5	Generally fair condition - potential exists for minor rehabilitation
4	Marginal condition - potential exists for major rehabilitation
3	Poor condition - repair or rehabilitation required immediately
2	Critical condition - the need for repair or rehabilitation is urgent. Facility should be closed until the indicated repair is complete.
1	Critical condition - facility is closed. Study should determine the feasibility for repair
0	Critical condition - facility is closed and is beyond repair

The total deficiency rating (TDR) can be calculated using the following equation (PennDOT, 1987):

$$TDR = \emptyset [LOSD + BCD + ORD] \quad (2.7)$$

where:

$LOSD = LCD + WD + VCOD + VCUD$

$BCD = SPD + SBD + BDD$

$ORD = RLD + AAD + WAD$

$\emptyset =$ functional classification factor (see Table 2.9).

Some limiting conditions to several combinations of deficiency points should be applied before calculating the TDR, these conditions are summarized in Table 2.10.

The determination of the TDR for each bridge is the first step in the prioritization process. Next, the estimation of costs for both replacement and rehabilitation, followed by determination of reduction in the TDR due to replacement and rehabilitation. In general, when the cost of rehabilitation exceeds 70 percent of the replacement cost, the replacement is recommended. The arrangement of all bridges in a decreasing order of TDR would generate a prioritized listing of bridge replacement and rehabilitation projects. PennDOT uses other indices besides TDR to develop its prioritized listing. The cost per daily vehicle user and the cost per unit of deficiency removed may be used as cost/benefit ratios.

2.4.2.3 Comparison of L.O.S. Priority Ranking Formulas

Many of the states have developed their own priority ranking formulas with different weights, in many cases patterned after North Carolina's formula. Table 2.11 presents the weighting factors given by five states to the major bridge attributes: load capacity, deck width, vertical clearance, condition and remaining life. North Carolina, Nebraska and Pennsylvania have assigned big weights to the load capacity because of the large number of posted bridges that they have.

Table 2.9 Functional Classification Factors

(Source: PennDOT, 1987)

Functional Classification	ϕ
Interstate	1.00
Arterial	0.95
Collector	0.85
Local	0.75

Table 2.10 Development of TDR for Bridges

(Source: PennDOT, 1987)

Deficiency Category	Maximum Deficiency Points in Category	Limiting Conditions			
		(1), (2)	(3)	(4)	
LCD	70	70			
BDD	50	} $\Sigma \leq 50$	} $\Sigma \leq 80$	} $\Sigma \times \phi \leq 100$	
SPD	50				
SBD	50				
WD	15	15	15		
VCOD	15	15	15		
RLD	15	5	5		
VCUD	10	} $\Sigma \leq 15$	15		
WAD	10				
AAD	10				
Maximum Totals:	285	180	140	100	

Bridge condition has big weights in the states with a significant number of bridges deficient in maintenance condition (Al-Subhi et. al., 1989). The behavior of the load capacity need functions for the five states are compared in Figure 2.3 (FHWA, 1989). North Carolina's need function is very sensitive to any deficiency up to 30 percent where it reaches its maximum. Pennsylvania's need function has the same rate of increase till 80 percent deficiency in the load capacity. Each state has its reasons for its formula, but the most important aspect of a priority ranking formula is that it reflects a state's particular circumstances in a reasonable way.

2.4.3 Incremental Benefit/Cost Analysis

This technique is based on economic principles and would select the improvement alternatives which are the most cost-effective. The incremental benefit/cost (B/C) technique has been used successfully at the project level to compare mutually exclusive alternatives. A computer program, called INCBEN, originally developed by McFarland et. al. (1983) to allocate funds on highway safety projects extends the incremental B/C analysis from the project level to the network level. To be feasible, the application of incremental B/C technique is recommended for a system with a small number of bridges.

The incremental B/C ratio can be defined as the extra total benefits gained by moving from one project to one higher in expenditure divided by the associated extra costs. The benefits used here include two types of benefits: agency benefits and user benefits. Agency benefits are defined as "the present worth of future cost savings to the agency because of a bridge expenditure", FHWA (1989). In other words, the benefits gained by an improvement that extends the bridge service life by (N) years is equal to the difference in the present worth of the replacement life cycle cost with and without the (N) years extension. The cost used to calculate the incremental B/C ratio is the present worth of the improvement alternative cost. User benefits can be considered in terms of cost reduction or savings to the user because of an improvement.

Table 2.11 State Weighting Factors

(Source: Al-Subhi et. al., 1989)

	N. Carolina (%)	Virginia (%)	Nebraska (%)	Kansas (%)	Pennsylvania (%)
Load Capacity	70	30	50	17	52
Deck Width	12	12	12	17	15
Ver. Clearance	12	12	33	--	8
Condition	6	46	10	55	25

Figure 2.3 Load Capacity Need Functions

(Source: FHWA, 1989)

For all alternatives, INCBEN calculates the incremental B/C ratio and asks for any undesirable alternatives to be rejected. Alternatives then are selected by INCBEN in descending order of their incremental B/C ratios until the granted budget is exhausted. Farid et. al. (1993) have applied the INCBEN program to a sample of 25 in-service bridges in North Carolina. It was concluded that INCBEN is superior to empirical priority ranking formulas because its decisions are based on sound economic principles.

2.4.4 Mathematical Programming Techniques

2.4.4.1 Indiana's Model

Mathematical Programming techniques have not yet been widely used in bridge management systems. Jiang and Sinha (1989) used an integer linear programming approach with a dynamic programming to formulate the model that will be described here. Three major rehabilitation activities were considered: deck reconstruction, deck replacement and bridge replacement. Deck reconstruction activity includes patching of deteriorated spots and an overlay of the deck after removing the wearing surface. Deck replacement activity includes the entire deck with rehabilitation of adjacent parts of the superstructure and the substructure. If the previous two activities failed to correct the existing deficiencies, then the replacement of the entire bridge will be recommended.

Each activity was defined as a zero-one decision variable; one if it is chosen and zero if not chosen. Hence, a routine maintenance is assumed for the unchosen bridges. The dynamic programming divides the problem into stages through which the system progresses. Each year is considered a stage. At each stage, the system is described by states which are the available budgets. At each stage, the Markov chain technique is used to predict the bridge condition, and an integer linear programming is used to maximize the effectiveness of the system. The constraints consist of the budget limits and the fact that one activity can be undertaken only once on one bridge in T years.

Effectiveness (Benefits) of the System was defined as a function of some variables: the condition rating improvement, average daily traffic (ADT), traffic safety conditions and community impact of a bridge, which was expressed in terms of detour length. Figure 2.4 illustrates the deterioration curve of a bridge with and without rehabilitation. The area between the two curves $A_i(a)$ represents an improvement in terms of the condition rating. It should be noted that for ratings 6 to 9, there is no need for rehabilitation. $[ADT_i * A_i(a)]$ can be interpreted as the measure of improvement that can be gained by the users of bridge (i). This measure was modified by two factors: the safety index and the detour length.

The effectiveness was expressed by the following formula (Jiang and Sinha, 1989):

$$E_i = [ADT_i * A_i(a)] * (1 + C_{safe,i}) * (1 + C_{impc,i}) \quad (2.8)$$

where

E_i = effectiveness gained by bridge (i) if activity (a) is chosen,

a = improvement activity = 1 for deck reconstruction,
2 for deck replacement, and
3 for bridge replacement,

ADT_i = average daily traffic on bridge (i),

$A_i(a)$ = equals to the average value of areas under performance curves of components of bridge (i) obtained by activity (a),

$C_{safe,i}$ = the transformed coefficient of traffic safety index. The safety index ranges from 1 to 10, with 10 for no potential traffic safety problem, and

$C_{impc,i}$ = the transformed coefficient of community impact of bridge (i) in term of detour.

Objective function:

$$Max \sum_{t=1}^T \Phi(Y(t)) \quad (2.9)$$

Figure 2.4 Area of Performance Curve Obtained by Rehabilitation
(Source: Jiang and Sinha, 1989)

Subject to:

$$\sum_{t=1}^T Y(t) \leq B \quad (2.10)$$

$$\sum_{i=1}^T X_{i,a}(a) \leq 1 \quad (2.11)$$

Where

$$\Phi(Y(t)) = \sum_i \sum_a X_{i,a}(a) * E_i * d_i(t) \quad (2.12)$$

$$Y(t) = \sum_i \sum_a X_{i,a}(a) * C_i(a) \quad (2.13)$$

$Y(t)$ = the amount of money spent in year t ,

$X_{i,a}(a)$ = 1, if bridge (i) is chosen for activity(a),
0 otherwise;

E_i = effectiveness gained by bridge (i),

$d_i(A)$ = the absolute tangent value on performance curve of bridge (i) at time t , which reflects the deterioration rate of bridge condition at time t ,

B = the available budget, and

$C_i(a)$ = estimated cost of activity (a) on bridge (i).

Dynamic Formulation:

Stages: the years from year 1 to year T .

States: the available budget (λ_t) at year (t) where:

$$\lambda_t = \lambda_{t-1} - Y(t+1) \quad (2.14)$$

Optimal return function:

$$g_1(\lambda_1) = \text{Max } \Phi_1(Y(1)) \quad (2.15)$$

$$g_t(\lambda_t) = \text{Max } [\Phi_t(Y(t)) + g_{t-1}(\lambda_t - Y(t))] \quad (2.16)$$

This forward recursion is performed for every successive year starting at year 1 until year T. Hence, the optimal spending policy and project selection from year 1 to year T can be obtained.

2.4.4.2 North Carolina's Model

An optimization model has been developed for North Carolina Department of Transportation by Al-Subhi et al. (1989). The model, called OPBRIDGE, intends to optimize the budget allocation to the bridge network by maximizing overall reductions in the equivalent uniform annual costs for all the bridges. The reductions will be compared to the alternative of replacement by a new bridge. The optimization problem is solved for every year separately by using an integer-linear programming formulation. The objective function is (Al-Subhi et al., 1989):

$$\text{Maximize } Z = \sum_{i=1}^{Nb} \sum_{j=1}^{NALT} REUAC(i,j,t) * X(i,j,t) \quad (2.17)$$

Where:

REUAC (i,j,t) = reduction in equivalent, uniform annual cost for improvement alternative j for bridge i, at year t,

X (i,j,t) = 1 if the alternative is selected and 0 otherwise,

Nb = number of bridges in the system, and

NALT = number of improvement alternatives.

The optimization is constrained by the budget constraints, L.O.S. constraints and minimum allowable condition rating constraints. Solving this integer programming problem,

with large number of decision variables ($N_b \times N_{ALT}$), is not an easy task. Enumeration methods and branch and bound method can not be used for such large problem. A heuristic technique was used to solve the problem. Such a technique would generate a good feasible solution but does not guarantee the optimal one.

2.5 Overview of Priority Setting Schemes

The sufficiency rating approach can be used as a reference for bridge management at the state level. The major drawback of SR is its insensitivity to highway classification and traffic volume. For two bridges of equal physical deficiency, but with great difference in traffic volumes, SR would not distinguish between them. Recognizing the drawbacks of the sufficiency ratings, level-of-service deficiency rankings have been developed. This approach incorporates the achievement of level-of-service goals to determine a bridge deficiency. Being sensitive to traffic volumes and highway classifications, this approach has proved to be superior to the sufficiency rating. The major advantages of this approach are its simplicity, the reliability of the data required and its applicability to a large number of bridges when compared to the incremental B/C technique or the available mathematical programming models. However, the L.O.S. deficiency ranking approach has two major limitations. First, it does not have the ability to determine the recommended action; major maintenance, rehabilitation or replacement. Second, it can not predict the best timing for any improvement action.

Estimation of user costs and prediction of future conditions are the major difficulties in applying the incremental B/C technique. The limitations of this method are that it can not be applied for a large number of bridges and can only be used over a relatively short budget period. Farid et al. (1993) stated that the incremental B/C technique is superior to empirical priority ranking methods. However, ranking bridge projects using their incremental B/C ratios is better than using L.O.S. priority ranking formulas, as it overcomes the first drawback

mentioned above, but it would not provide optimal solutions. This is because it lacks this ability to optimize the system benefits. The incremental benefit/cost method still suffers from the second drawback of the L.O.S. ranking method. It also assumes that the benefits gained from an improvement action are constant if the projects were to be undertaken now or at any time within the analysis period, but this is not a correct assumption. The incremental B/C analysis can be used in comparing different improvement actions for the same bridge, i.e. at the project level.

Priority ranking and incremental B/C techniques do not guarantee optimal solutions. Mathematical programming models manipulate the tradeoffs between the objective and constraints systematically, so that an optimal solution can be reached. However, the model developed by Jiang and Sinha (1989) has a deficiency in its formulation. This deficiency is to equate the states of each stage with its decision. The Integer Programming technique is used at each state, but this technique will not provide optimal solutions for a large number of decision variables. The model also assumed the effectiveness of the system to represent only the user benefits and ignored the agency benefits. The user benefits are represented by the average daily traffic (ADT) multiplied by the area between the two deterioration curves; with and without rehabilitation. This representation needs more supportive reasons. The model assumes that the effectiveness of carrying out an improvement action depends only on the bridge condition without considering the accumulated costs due to delaying these actions. The model is limited to choosing only between three, previously defined, improvement alternatives for each bridge and for a maximum of 1,000 bridges.

The North Carolina's model (OPBRIDGE) correctly defined the system benefits using a study conducted by Chen and Johnston (1987). OPBRIDGE, like Indiana's model, is limited to choosing only between three improvement alternatives for each bridge, but it overcomes the limitation of the 1,000 bridges and can handle over 14,000 bridges. The model has the advantage of including the L.O.S. goals as constraints to the optimization problem. The main weakness of the model is the fact that integer programming can not be solved exactly for a large number of decision variables hence heuristic techniques are used.

These techniques generate good feasible solutions but not an optimal solution. The model also does not have the ability to find the optimal timing for each project.

2.6 Summary

In this Chapter, a comprehensive review has been presented. As discussed, bridge management appeared in the form of establishing databases for bridges. Later, individual states in the U.S. began to develop some bridge management concepts and procedures. North Carolina and Pennsylvania were the leaders in this field. Recognizing the importance of Bridge Management Systems, the FHWA sponsored the development of "Pontis", the first complete BMS software. "Pontis" system was reviewed in this Chapter and its major drawbacks were identified. In spite of the fact that "Pontis" suffers from some major drawbacks, it provided the first concrete step in developing a comprehensive BMS. As indicated by a questionnaire survey, conducted by the New York DOT, most of the U.S. states and some Canadian provinces intend to adopt "Pontis".

Priority setting schemes for bridge rehabilitation and replacement projects represent the core of a BMS. The available schemes were reviewed and their advantages and disadvantages were identified. The review resulted in the conclusion that the available schemes can not generate the optimal decision for allocating limited budget to bridge projects and there is an urgent need for a better scheme that can fulfill this function.

After reviewing the state-of-the-art of BMS, it is concluded that the existing BMS frameworks do not satisfy the needs of bridge networks. Therefore, the next Chapter will present a comprehensive framework for a BMS that will be developed through the remainder of the thesis. It is believed that the developed system avoids the drawbacks of "Pontis", integrates all bridge related activities, utilizes state-of-the-art available technology, and considers the influence of rehabilitation projects on maintenance activities.

CHAPTER 3

A COMPREHENSIVE FRAMEWORK FOR BRIDGE MANAGEMENT SYSTEMS

3.1 Introduction

Little research work has been done to examine the bridge management issue on a comprehensive basis. "Pontis", as a representative of the state-of-the-art of a complete BMS, was reviewed in Chapter 2 and its main drawbacks were identified. However, "Pontis" provided the first concrete step in developing a comprehensive BMS. An attempt is made here to develop a comprehensive framework for a BMS in order to overcome the drawbacks of "Pontis" and to fulfil the functions required by a BMS. The developed framework integrates existing procedures for bridge management, adopts certain principles from pavement management and establishes new modules.

The main goal of the BMS is to integrate all bridge activities in such a way that it utilizes the available resources in the most effective manner. In this thesis, bridge activities were divided into two main groups; rehabilitation and replacement (R&R) projects and maintenance activities. Rehabilitation and replacement projects include replacing the whole bridge or any action to raise its overall level-of-services (L.O.S). Maintenance activities are those activities which can be carried out by the agency maintenance crews. The objective of the system is to allocate the available budget and resources to R&R projects and maintenance activities and to determine the optimum timing for each project or activity over a certain period of time. The influence of R&R projects on maintenance activities will be considered by the system. The system may be considered as a decision-support tool for managing a network of bridges.

In this Chapter, the main modules of the developed system will be delineated by identifying their functions and the interaction among them. Figure 3.1 illustrates the BMS framework. The system incorporates the following nine main modules:

- 1) Database Module
- 2) Prediction Module
- 3) L.O.S. Module
- 4) R&R Expert Module
- 5) Alternative Analysis Module
- 6) R&R Network Optimization Module
- 7) Maintenance Expert Module
- 8) Maintenance Optimization Module
- 9) Monitoring and Updating Module

The following sections discuss the nine modules in more detail.

3.2 Database Module

The database represents the links among all the BMS modules. Every bridge in the network should be described in the database and the modules output should also have appropriate files in the database. The effectiveness of the system relies greatly upon the design of the database scheme. The system output is as good as the available database, but "goodness" does not mean a large amount of data. The most important indicator of "goodness" is the significance of the data items. An appropriate database management software should be selected to handle the system data. Due to record orientation of data, it is recommended that a relational database be used to model the pertinent data. Identification of data requirements and the design of database scheme will be presented in Chapter 7.

Figure 3.1 The Developed Bridge Management System Framework

3.3 Prediction Module

The main function of this module is to predict future parameters using some prediction models which have been calibrated using historical data gathered by the BMS. Three groups need to be predicted: future bridge conditions, rehabilitation and replacement activity costs and traffic parameters.

Markov Chain approach has been widely used to predict pavement conditions. Jiang and Sinha (1989) have developed a prediction model for bridge condition rating using the same technique. The Markov Chain assumes that future deterioration does not depend on the bridge history. Instead, it assumes that future deterioration depends only on "the present condition of the bridge and a known probability of the change in bridge condition over a specified period" (Sobanjo, 1993). It was observed that the deterioration rates during the last stages of a bridge life are higher than those for young bridges (Hyman et al., 1983). Therefore, the application of Markov Chain to bridges should be carefully investigated.

Statistical regression-based models is another alternative for predicting future bridge conditions. According to the observation of Hyman et al. (1983), it is recommended to use piecewise models (Sobanjo, 1993). This means dividing the bridge life into two or three intervals and calibrating the models for each interval. PennDOT (1987) has developed for reinforced concrete bridges regression-based models relating condition rating and load capacity to bridge age. The following equations were calibrated using data from Pennsylvania. Three equations were developed for bridge condition rating (CNR) which range from 0 to 9, with 9 for new bridges. Two equations were also developed to predict the load capacity (LC) in tons (PennDOT, 1987):

$$CNR = 9 (1 - A)^{0.7} \quad (0 \leq A \leq 0.79) \quad (31)$$

$$CNR = 10.7073 - 9.7339 A \quad (0.79 \leq A \leq 1.1) \quad (32)$$

$$CNR = 0 \quad (A \geq 1.1) \quad (33)$$

$$LC = LC_D [1 - (A/1.1)^5] \quad (0 \leq A \leq 1.1) \quad (34)$$

$$LC = 0 \quad (A > 1.1) \quad (35)$$

Where:

A = (bridge element age at prediction year) / (its estimated service life),

LC = predicted load capacity, and

LC_D = design load capacity.

However, it is also recommended to include traffic volume, highway classification and bridge climatic region in order to develop piecewise models for each type of bridges.

The second group of parameters to be predicted is the cost and duration of rehabilitation and replacement projects. The data collected by the Monitoring and Updating Module will be used to establish unit costs for all rehabilitation and replacement activities. Duration of all activities should also be estimated. Expenditure variations from region-to-region should be taken into consideration.

The last group is the traffic parameters. Traffic models developed by the agency or any other organization in the region can be used to predict future traffic volumes and percentage of truck traffic. Truck load distribution is important to predict the percentage of vehicles detoured for different levels of bridge posting along with different ranges of vertical clearance. Accident data would be analyzed to construct relations between accident rates and deck width and alignment deficiencies. Quantification of travel time, vehicle operating costs and accident cost requires models calibration using data from each region separately.

The complete development of this module is out of the scope of this thesis. As seen from the previous discussion, models for predicting future bridge conditions are available and can be employed in the BMS. However, this area is still in need of further research. Cost models should be calibrated for each province or region to reflect its own conditions. The available traffic models, developed by local agencies, can be used by the BMS.

3.4 Levels-of-Service Module

In the past the L.O.S. goals were not considered as an independent module. In this thesis, these goals have been recognized as an important aspect of the overall management strategies and therefore have been integrated into an independent module. The main function of this module is to give access to the user agency to set its own levels-of-service goals. The four L.O.S. groups that have been defined in this study are:

- 1) **Rehabilitation and replacement L.O.S.:**
 - Load capacity (acceptable and desirable)
 - Lane width (acceptable and desirable)
 - Shoulder width (acceptable and desirable)
 - Vertical clearance (acceptable and desirable)
- 2) **Routine maintenance L.O.S.:**
 - Routine maintenance activity description
 - Frequency of activity
- 3) **Preventive maintenance L.O.S.:**
 - Preventive maintenance activity description
 - Percentage of damage, when exceeded activity is performed
- 4) **Maintenance suspension periods.**

The fourth group will be discussed in detail in Chapter 6.

3.5 R&R Expert Module

The main flaw of the most recently developed BMS is the elimination of the engineering expertise from the process. The purpose of incorporating this module into the Bridge Management System is to substitute the human engineering expertise by an artificial expert system. "The term 'expert system' is used to refer to a computer system or program which incorporates one or more techniques of Artificial Intelligence (AI) to perform a family

of activities that traditionally would have to be performed by a skilled or knowledgeable human" (Tanimoto, 1987). The advantages of using a knowledge-based expert system are that artificial expertise is permanent, easy to upgrade and to document, consistent and affordable. Expert systems differ from conventional programs in manipulating knowledge instead of data.

The main members of the expert system building process are shown in Figure 3.2 and they are: the domain expert, the knowledge engineer and the expert system building tool or shell. The main function of this module is to generate all the possible improvement alternatives for a bridge when supplied by the bridge condition data. The module will have its input from all of the Database, Prediction and L.O.S. modules. The output of the module will be forwarded to the Alternative Analysis module.

The R&R Expert Module is newly defined here in this study, but the complete development of this module is out of the scope of this thesis.

3.6 Alternative Analysis Module

This module was developed, through out this study, in order to prepare the input file for the R&R Network Optimization module. This requires estimating the loss of system benefits as well as the initial costs associated with all improvement alternatives for every bridge in the network. The module will have input from the Prediction Module and the R&R Expert Module. The initial costs of different alternatives will be estimated by multiplying the quantities of work required by their unit costs. The loss of system benefits will be calculated from two sources: first, the agency benefit loss, and second the user benefit loss.

The benefit loss associated with carrying out any improvement alternative is defined by the following equation:

Figure 3.2 Members of the Expert System Building Process

(Source: Waterman, 1986)

$$BL(t, B, A) = [(LCC(t, B, A) - LCC(t, B, E)) + (UC(t, B, A) - UC(t, B, E))] * (P/F, r, t) \quad (3.6)$$

Where:

$LCC(t, B, A)$ = perpetual life cycle cost of alternative A for bridge B if done at year t,

$UC(t, B, A)$ = user costs for alternative (t, B, A),

E = alternative for bridge B at year t that has minimum (LCC + UC), and

$(P/F, r, t)$ = present worth factor for real rate of return r and t years.

Equation (3.6) states that the benefit losses associated with carrying out an improvement alternative (A) for bridge (B) at year (t) includes two parts: the agency benefit loss and the increased user cost. The agency benefit loss was defined to be the difference between the LCC of alternative (t, B, A) and alternative (t, B, E). The user benefit loss was defined to be the difference between the user cost of alternative (t, B, A) and alternative (t, B, E). Alternative (t, B, E) is defined to be the alternative which has the minimum (LCC + UC). The optimal decision for this single bridge (B) is to carry out alternative (E) but according to budget constraints it may not be the optimal decision if the objective is to minimize the benefit losses for the whole network. The user cost will be defined in this section. A typical bridge LCCs will also be presented in a later part of this section. All the analysis associated with agency benefit loss and the user benefit loss will be carried out based on the present worth method.

The user cost was defined to be the sum of two parts. First one is the increase in user costs due to levels of service deficiencies, and the second is the user cost due to traffic delay during construction. Levels of service deficiencies may be in the form of: narrow width, poor alignment, low vertical clearance or low load capacity. A study conducted by Chen and Johnston (1989) assumed that user costs increase linearly with traffic volume and the level-of-service deficiency of a bridge. The following equations were derived to estimate the increase

in user costs due to L.O.S. deficiencies (Chen and Johnston, 1989):

$$AUL = DWDC + ALDC + CLDC + LCDC \quad (3.7)$$

$$DWDC = C_{WDA} * U_{AC} * ADT * 365 \quad (3.8)$$

$$ALDC = C_{ALA} * U_{AC} * ADT * 365 \quad (3.9)$$

$$CLDC = [(C_{CLA} * U_{AC}) + (C_{CLD} * U_{DL} * DL)] * ADTT * 365 \quad (3.10)$$

$$LCDC = C_{LCD} * U_{DL} * DL * ADTT * 365 \quad (3.11)$$

Where:

AUL	=	annual user cost due to L.O.S. deficiencies,
DWDC	=	deck width deficiency cost,
ALDC	=	alignment deficiency cost,
CLDC	=	vertical clearance deficiency cost,
LCDC	=	load capacity deficiency cost,
C_{WDA}	=	percentage of vehicles incurring accidents due to deck width deficiency,
C_{ALA}	=	percentage of vehicles incurring accidents due to alignment deficiency,
C_{CLA}	=	percentage of trucks incurring accidents due to clearance deficiency,
C_{CLD}	=	percentage of trucks detoured due to clearance deficiency,
C_{LCD}	=	percentage of trucks detoured due to a load capacity deficiency,
U_{AC}	=	average cost of an accident (\$/accident),
U_{DL}	=	cost of one kilometre detoured (\$/Km),
DL	=	detour length (Km),
ADT	=	average daily traffic using the bridge, and
ADTT	=	average daily truck traffic using the bridge.

The second part is the user cost due to traffic delay during construction. This part

may be highly significant on long bridges with high traffic volumes. Figure 3.3 shows the relationship between travel time cost and speed. The figure illustrates how low speeds would increase travel time costs. The following equation was established to estimate the incurred costs due to delay during construction:

$$UD = ADT * D * (TC_{v_1} - TC_{v_2}) * L \quad (3.12)$$

Where:

- UD = user cost due to traffic delay during construction,
- ADT = average daily traffic using the bridge,
- D = duration of construction,
- TC = unit travel time cost (\$/vehicle.Km),
- V1 = traffic speed during construction,
- V2 = normal traffic speed, and
- L = bridge length.

It should be noted that eqn(3.12) represents a simple form and the available traffic delay models which are developed by local transportation agencies are better to be employed. The total user costs was defined by adding the costs due to L.O.S. deficiencies and the costs due to traffic delay during construction:

$$UC = AUL * (P/A, r, m) + UD \quad (3.13)$$

Where:

- UC = present worth of total user cost,
- AUL = annual user cost due to L.O.S. deficiencies,
- UD = increased user cost due to traffic delay during construction,
- (P/A, r, m) = series present worth factor for real rate of return r and m years, and
- m = number of years until L.O.S. deficiencies will be eliminated.

Figure 3.3 Quantification of Travel Time Costs

The R&R Expert Module will construct life cycle activity profiles for the proposed alternatives. This requires knowledge of bridge history and bridge condition. Alternative Analysis Module will combine each life cycle activity profile with its appropriate cost parameters to estimate its perpetual life cycle cost and perpetual user costs. To illustrate how the life cycle costs and the user costs to be calculated two different improvement alternatives were assumed for a bridge. Figure 3.4 shows the life cycle cost profile and the user cost profile for an improvement alternative, which was named A. Figure 3.5 shows two profiles for another alternative, named E. Alternative E was assumed to be the alternative that has the minimum (LCC + UC).

Alternative A suggested that the bridge will be rehabilitated at year (t). This rehabilitation will extend its service life by (e) years, after which it will be replaced. Then this cycle will be repeated every (e + SL) years. The annual maintenance costs are assumed to be constant after the bridge has been rehabilitated. After replacement the maintenance costs profile will be as shown in Figure 3.4. The annual user cost is assumed to be U_1 after rehabilitation, then it will decrease to be U_2 after replacement. The life cycle cost and the user cost that to be used in eqn(3.6) will be estimated using the following equations.

$$LCC_A = [(RB + M_1 (P/A, r, e)) + ((RP - S) + M_2 (P/A, r, SL) + G (A/G, r, SL) (t/A, r, SL)) * (P/F, r, e)] * (PPWF, r, (e + SL)) \quad (3.14)$$

$$UC_A = [(UD_{RB} + U_1 (P/A, r, e)) + (UD_{RP} + U_2 (P/A, r, SL)) * (P/F, r, e)] * (PPWF, r, (e + SL)) \quad (3.15)$$

Where:

- LCC_A = perpetual bridge life cycle cost for alternative A,
- RB = rehabilitation costs,
- M_1 = annual maintenance cost after rehabilitation,
- RP = replacement costs,

Figure 3.4 Cost Profiles for Alternative (A)

Figure 3.5 Cost Profiles for Alternative (E)

- S** = salvage value of old structure,
M₂ = annual maintenance cost after replacement,
G = gradient series of increased maintenance costs due to deterioration,
e = extended life due to rehabilitation,
SL = average bridge service life,
UC_A = perpetual user cost for alternative A,
U₁ = annual user cost for alternative A after rehabilitation, defined by eqn(3.7),
U₂ = annual user cost for alternative A after replacement, defined by eqn(3.7),
UD_{RB} = user cost due to delay during rehabilitation, defined by eqn(3.12),
UD_{RP} = user cost due to delay during replacement, defined by eqn(3.12),
(P/A, r, e) = series present worth factor for real rate of return (r) and (e) years,
(A/G, r, SL) = arithmetic gradient series present worth factor for real rate of return (r) and (SL) years,
(P/F, r, e) = present worth factor for real rate of return (r) and (e) years, and
(PPWF, r, SL) = perpetual present worth factor for real rate of return (r) and (SL) intervals.

The alternative E for the same bridge was assumed to be replacing the old bridge by a new one at year t. Figure 3.5 shows the life cycle cost profile as well as the user cost profile for alternative E. The life cycle cost and user cost for alternative E are to be calculated using the following equations:

$$LCC_E = [(RP - S) + M_2 (P/A, r, SL) + G (A/G, r, SL) (P/A, r, SL)] * (PPWF, r, SL) \quad (3.16)$$

$$UC_E = [UD_{RP} + U_2 (P/A, r, SL)] * (PPWF, r, SL) \quad (3.17)$$

Using equations 3.14 to 3.17, the benefit loss defined by eqn(3.6) can be estimated for all alternatives for all bridges. The function of the Alternative Analysis Module, as mentioned earlier is to prepare the input file for the R&R Network optimization Module.

This file requires information about all possible alternatives for each bridge, if the bridge to be repaired at any year of the analysis period. Figure 3.6 illustrates the development of this file. As shown in the figure, the Prediction Module and the R&R Expert Module cooperate with the Alternative Analysis Module to prepare this file. It should be noted that T is the length of the analysis period, N is the total number of bridges, t refers to the years and B refers to the bridges.

3.7 R&R Network Optimization Module

This part of the BMS is primarily concerned with the rehabilitation and replacement projects only, which consumes most of the funds assigned to bridges. Replacement means replacement of the whole bridge with a new one. The definition of "rehabilitation" may vary from agency to another. However, rehabilitation is defined here to be any action carried out on a certain bridge to raise its overall Level-of-service and may include changing the original structure. Thus, rehabilitation activities will include all those projects that can not be handled by maintenance crews.

The cost of rehabilitation and replacement (R&R) of bridges consumes most of the funding available for bridge improvements. Therefore, the budget required for those activities must be carefully allocated. Priority Setting Schemes currently used for allocating budget to R&R activities have been reviewed in Chapter 2. The review indicated that there is a need for an efficient priority setting scheme which can utilize the available limited funds in the most cost-effective manner. The development of a network optimization model for bridge R&R activities is one of the main objectives of this research and will be presented in Chapter 4.

Figure 3.6 Development of the Input File

3.8 Maintenance Expert Module

The Maintenance Expert Module is clearly identified here in this study as a new component of the BMS. The main components of this module and their functions will be identified. The definition of "maintenance" varies from agency to another. Broadly speaking, it is any action that is performed by the agency maintenance crews and aims to avoid premature deterioration. Maintenance activities can be divided into two main groups; routine maintenance and preventive maintenance (Manning and Reel, 1986).

The first step in managing bridge maintenance is to determine the required activities for the whole network. This is the function of the Maintenance Expert Module. This module will contain four sub-modules to perform its function. Figure 3.7 illustrates the components of the Maintenance Expert Module. The module will receive input including; bridge conditions and dates of last maintenance activities. The maintenance standards may vary from one province to another, thus the L.O.S. Module was introduced in order to facilitate adjusting those standards. As shown in Figure 3.7, the Updating Sub-Module will perform the first step, which is to update the dates of last maintenance activities according to the maintenance activity list of the previous year, which has been generated by the Maintenance Optimization Module. Note, as will be explained in Chapter 6, the maintenance optimization process will be performed for each year separately. After this step, the bridge data will be forwarded simultaneously to two sub-modules; the Routine Maintenance Expert Sub-Module and the Preventive Maintenance Expert Sub-Module. Each one of these sub-modules is an expert system. Routine maintenance activities include, but are not limited to, the following activities:

- Flushing bridge deck
- Cleaning and sealing of deck joints
- Drift removal
- Cleaning and sealing of bearing
- Cleaning of drainage system
- Maintenance of slopes and shore protection system
- Handrail painting
- Brush control at bridge site

Figure 3.7 The Maintenance Expert Module

Preventive maintenance activities include, but are not limited to, the following:

- Deck patching
- Crack sealing
- Spot painting
- Sealing concrete surfaces
- Handrail repair
- Refastening of steel plate joints
- Repair of drainage parts
- Minor pier or abutment repair

Both of these sub-modules will generate a list of the recommended maintenance activities. The two lists will be provided as input to the last sub-module, which is called the Performance Sub-Module. The function of this sub-module is to quantify the maintenance needs in terms of labour and equipments. When running the BMS for the first time, the performance rates used to construct this module can be obtained from the agency maintenance staff. After a short while, the performance rates can be obtained from the historical data kept by the system. The output of the Maintenance Expert Module will include a list of the required maintenance activities associated with their requirements of labour and equipments expressed by the required "Crew-Hours" for each activity.

3.9 Maintenance Optimization Module

Maintenance activities have been defined in the previous section. The objective of performing these activities is to provide bridges with certain maintenance standards in order to avoid premature deterioration. According to these standards and bridge conditions, the required maintenance activities for the whole network will be identified by the Maintenance Expert Module. The function of the Maintenance Optimization Module is to allocate the available resources of labour and equipment to the required activities in order to maximize the system benefits. The output of this module will include a list of the recommended activities for each year of the analysis period. The problem of managing bridge maintenance is different from the problem of managing rehabilitation and replacement projects. The

differences will be identified and an optimization module will be developed. The influence of rehabilitation and replacement decisions on maintenance planning will be considered by this module. The details of this module, as one of the main objectives of this research, will be presented in Chapter 6.

3.10 Monitoring and Updating Module

The function of this module was introduced by Hudson et al. (1987). This module works as a user interface tool in order to record three groups of information and store them in appropriate files in the database. The three groups identified in this thesis as follows: inspection information, the performed maintenance activities information and the rehabilitation and replacement projects' records.

Inventory inspection is held when the database is being constructed, when a new bridge becomes a part of the bridge inventory or when the structure configuration has been changed. Routine inspection will be regularly scheduled to determine the physical and functional condition of the bridge. In-depth inspection may be required if it is recommended by a routine inspection. Most of the transportation agencies have their own inspection forms. However, PennDOT (1987) provides a comprehensive bridge inspection form. Bridge conditions will be provided continuously to the database in order to form the historical data required for the prediction module.

All the performed maintenance activities should be properly recorded. These records can be used to estimate future maintenance requirements and the effectiveness of maintenance activities. The following items should be recorded for each maintenance activity:

- Bridge identification number
- Date recommended by the BMS to carry out this activity
- Date of carrying out the activity
- Activity name
- Activity code

- Resources used (crew-hours)
- Quantities of work done (e.g. patching 5 m² of bridge deck)
- Exact materials, labour and equipment used
- Any comments

All rehabilitation and replacement projects should also be carefully documented. This information can be used to estimate future costs and deterioration rates. The following items should be recorded for each project:

- Bridge identification number
- Date recommended by the BMS to carry out this activity
- Date of starting the project
- Completion date
- Exact project duration excluding any external delay
- Project title
- Activity code
- Contract number
- Name of general contractor
- Total cost of the project
- Amount of work done coded in appropriate units

3.11 Summary

This Chapter presented the BMS framework which was developed through out this study. The system incorporates nine main modules. These modules can be grouped, according to their development status into three groups:

A) Modules developed through out this study:

- The DataBase Module
- The Alternative Analysis Module
- The R&R Network Optimization Module
- The Maintenance Optimization Module

B) Modules newly defined, but complete development was out of the scope of the thesis:

- The R&R Expert Module
- The Maintenance Expert Module

C) Modules adopted from previous studies:

- The Prediction Modules
- The Levels of Service Module
- The Monitoring and Updating Module

The Alternative Analysis Module was presented in this Chapter, while the rest of category A modules are presented in the upcoming Chapters. The Database Module is presented in Chapter 7, the Maintenance optimization Module is presented in Chapter 6, and the development of the R&R Network Optimization Module is presented in the next two Chapters.

CHAPTER 4

DEVELOPMENT OF A NETWORK OPTIMIZATION MODEL FOR REHABILITATION AND REPLACEMENT PROJECTS

4.1 Introduction

After reviewing the different kinds of schemes for setting priorities for bridge rehabilitation and replacement projects, and considering the fact that ranking formulas, including incremental B/C ratio, do not guarantee optimal solutions, it is believed that mathematical programming techniques would provide better models. Ranking techniques sort projects in descending order of their ranking index, which is estimated through evaluation of several factors for each project. Each year the ranking index is established for all bridges and those projects at the top of the list and within the available budget are recommended for implementation. Such a technique can not optimize the system benefits while mathematical programming methods manipulate the tradeoffs between the objectives and constraints systematically, so that an optimal solution can be reached. Two mathematical programming models were reviewed, but they have some drawbacks as discussed in Chapter 2. Nevertheless, they helped in understanding the problem.

Despite the fact that allocating budget to bridge projects is a multi-period optimization problem, none of the available methods can perform such function. Therefore, it is the objective of this Chapter to present a model, developed through out this study, that can perform multi-period optimizations.

Due to the fact that the bridge problem has two dimensions; the time dimension and the network dimension and because of the large number of decision variables involved, the

dynamic programming approach was selected herein to formulate the optimization model. This chapter will discuss the formulation of this model. The model function is to allocate the available budget to bridge replacement and rehabilitation projects over a certain period of time. The application of the model will be demonstrated and a comparison between the developed model and the incremental benefit/cost method will be performed.

Dynamic programming (D.P.) provides a recursive approach to solving optimization problems by making a sequence of interrelated decisions. The power of the D.P. comes from its capability to reject those combinations that can not generate an optimal solution and examines only a subset of all possible combinations. A major drawback of the D.P. is that if the problem is not formulated correctly, one can not utilize the power of the D.P. and the generated solution may not be the optimal one. There is no specific algorithm to solve D.P. problems, as the simplex method is used for solving linear programming problems or the branch-and-bound method for integer programming problems. Dynamic programming approach can be generally described in five steps (Chinneck, 1992):

- 1) Divide the problem into smaller parts or stages.
- 2) Begin with one stage and find its optima.
- 3) Enlarge the problem and continue finding its optimal solution using previous optima.
- 4) Repeat step (3) until solving the entire problem.
- 5) From final result back track the solution.

These steps provide a simplified description for dynamic programming. In reality, dynamic programming formulation is not an easy task.

4.2 Model Formulation

The objective of the model is to allocate the available budget to bridge replacement and rehabilitation projects in order to minimize the loss of the system benefits. Budget allocation to bridge projects include choosing the best improvement alternative for each bridge in the network with determining the optimum timing for carrying it out. The general

objective function was defined as follows:

$$\text{Minimize } Z = \sum_{t=1}^T \sum_{B=1}^N \sum_{A=0}^{m(t,B)} BL(t, B, A) * X(t, B, A) \quad (4.1)$$

Where:

$Z =$ the total loss of system benefits;

$T =$ analysis period in years;

$N =$ total number of bridges;

$m(t,B) =$ number of improvement alternatives for bridge (B) in Year (t);

$BL(t,B,A) =$ the amount of loss of system benefits if alternative (A) for bridge (B) was chosen in year (t); and

$X(t,B,A) =$ 1 if alternative A was chosen and 0 otherwise.

The Alternative Analysis Module will be responsible for the estimation of the initial costs and benefit losses for all possible alternatives for each bridge, if the bridge is to be repaired at any year of the analysis period. The details of this Module have been discussed in Chapter 3. The benefit loss associated with carrying out any improvement alternative was defined by eqn(3.6). The development of the whole input file for the R&R Network Optimization Module was discussed also in Chapter 3. The model is formulated, as mentioned earlier, using a dynamic programming approach. Actually, it is two dynamic programming models combined together. The outer model will set years as its stages, while the inner model will handle the bridges as its stages.

4.2.1 The Outer Model

As mentioned earlier, there is no specific algorithm to solve the dynamic programming problems, as the simplex method is used for solving linear programming problems. However, the objective of the model can be represented by eqn(4.1). For each year, there is an available budget of BD \$/year that can be carried over to any of the following year. The

total budget (TBD) for an analysis period of T years can be calculated by the summation of the annual budgets over T. The spending level at each year should not exceed the budget of that year plus accumulated money from previous years. This can be expressed by the following equation:

$$\sum_{j=1}^{j=t} \sum_{B=0}^N \sum_{A=0}^{m(B,A)} IC(j, B, A) * X(j, B, A) \leq \sum_{j=1}^{j=t} BD_j$$

for all t (4.2)

Where:

IC (j,B,A)= initial cost of alternative (A) for bridge (B) if done in year (j);

X (j,B,A) = 1 if alternative (A) for bridge (B) was chosen in year (j), and 0 otherwise; and

BD_j = the available budget for year (j).

Dynamic Programming Formulation

Stages (t): years from year 1 to year T (Forward Recursion).

Decision at a stage: what is the optimum spending level at this stage in order to minimize the loss of system benefits.

States (d): all possible levels of budget that can be carried for the next year.

Decision update to state: given that the spending level is w_t \$/year, which bridge projects are to be implemented.

Recursive value relationship:

$$f_t(d_t) = \text{Minimum } [g(t, d_t, w_t)] \text{ for all } w_t \quad (4.3)$$

$$g(t, d_t, w_t) = BL(t, d_t, w_t) + f_{t-1}(d_t + w_t - BD) \quad (4.4)$$

Where:

f_t(d_t) = the minimum benefit loss that can be achieved till stage (t) at state (d_t);

g(t,d_t,w_t) = benefit loss till stage (t) at state (d_t) when spending level is w_t \$/year; and

BL(t,d_t,w_t)= benefit loss for stage (t) at state (d_t) when spending level is w_t \$/year.

At each stage (t), there will be a matrix with (d_i)s as its rows and (w_i)s as its columns. The matrix elements are the values of g (t,d_i,w_i). Each element of this matrix requires two parts as seen in eqn(4.5); the second part will be obtained from the previous stage (t-1), while the first part will be solved by the Inner Model. The decision of the Inner Model Dec (t,d_i,w_i) for this element will include three parts:

- 1) D (t,d_i,w_i): The set of bridge projects to be carried out at stage (t) and state (d) if spending level is w_i. Each bridge will be described by a vector {B, A, k}.

Where:

B = the bridge ID;

A = the alternative to be carried out; and

k = the year at which the bridge can be reconsidered for another improvement, and it equals (t + v).

where:

v = the number of years after which the bridge can be reconsidered if alternative (A) was chosen, and it will be provided to the model.

- 2) BL (t,d_i,w_i): Loss in system benefits due to carrying out the set of projects D (t,d_i,w_i).
- 3) IC (t,d_i,w_i): The initial costs of carrying out the set of projects D (t,d_i,w_i).

It should be noted that the model will begin with all the network bridges at stage (1). At any successive stage (t), the bridge population P (t,d_i,w_i) which will be used by the inner model to solve the cell (t,d_i,w_i) can be defined as follows:

$$P (t,d_i,w_i) = P (t-1, d_i+w_i-BD, w_{i-1}^*) - D (t-1, d_i+w_i-BD, w_{i-1}^*) \quad (4.5)$$

Where:

W_{i-1}^* = the spending level corresponding to $f_{i-1} (d_i+w_i-BD)$.

In fact, the calculations of P (t,d_i,w_i) will be performed by updating the k values for all the bridges. If (k ≤ t) then the bridge will be included in P. After solving the inner model the k values will be updated in D (t,d_i,w_i) as follows:

k = k if Do Nothing alternative was chosen; and

k = t + v otherwise.

4.2.2 The Inner Model

This model is developed using a dynamic programming technique which was originally adopted by Brown and Colson (1975) and modified by Pigman et al. (1976) in order to develop a model for assigning priorities to highway safety projects. The model is used at each element (t, d_t, w_t) of the Outer model in order to get the optimal decision for that element; $\text{Dec } (t, d_t, w_t)$. The input to the model will include all the bridge data of the set P (t, d_t, w_t) as well as the available budget which is $(\$ w_t)$. The objective function of the model and its constraints is defined as follows:

$$\text{Minimize } Z = \sum_{B=1}^N \sum_{A=0}^{m(B)} BL(B, A) * X(B, A) \quad (4.6)$$

Subject to:

$$\sum_{B=1}^N \sum_{A=0}^{m(B)} IC(B, A) * X(B, A) \leq W \quad (4.7)$$

$$\sum_{A=0}^{m(B)} X(B, A) = 1 \quad \text{for all } B \quad (4.8)$$

$$X(B, A) = 1, 0 \quad (4.9)$$

Where:

- $Z =$ the benefit loss for any stage (t) at any state (d_t) of the Outer model, when spending level or available budget equals W \$/year;
- $N =$ total number of bridges;
- $m(B) =$ number of improvement alternatives for bridge (B) ;
- $BL(B, A) =$ the loss in system benefits if alternative (A) was chosen for bridge (B) ;
- $X(B, A) =$ 1 if alternative (A) was chosen for bridge (B) and 0 otherwise; and
- $W =$ the available budget (\$/year).

Dynamic Programming Formulation

Stages (B): bridges from bridge 1 to bridge n (Forward recursion).

Decision at a stage: what is the improvement alternative for that bridge (stage) which minimize the loss of system benefits.

States: available budget.

Decision update to state: given that alternative (A) is to be chosen, what is the loss in system benefits.

Recursive value relationship:

$$f_B (S_B) = \text{Minimum} [v (B, S_B, A_B)] \quad \text{for all } A_B \quad (4.10)$$

$$v (B, S_B, A_B) = BL (A_B) + f_{B-1} (S_B - IC (A_B)) \quad (4.11)$$

Where:

$f_B (S_B)$ = the minimum benefit loss that can be achieved till stage (B) at state (S_B);

$v (B, S_B, A_B)$ = benefit loss till stage (B) at state (S_B) when alternative (A_B) is chosen;

$BL (A_B)$ = benefit loss if alternative (A_B) is chosen for bridge (B); and

$IC (A_B)$ = initial cost of alternative (A_B).

The states at each stage begin from zero and increase in increments until they reach the available budget W_i . This increment should be chosen so that the project costs will be multiples of it. At each stage (B), there will be a matrix with S_B 's as its rows and A_B 's as its columns. The matrix elements are the values of $v (B, S_B, A_B)$.

4.3 Demonstration for the Outer Model

This section demonstrates how dynamic programming works to solve the bridge problem through a hypothetical example. The analysis period for this example will be 5 years for a network of N bridges. The Outer model is not affected by the number of bridges

but it is affected by the length of the analysis period and the annual budget which in this case is \$3 Million/year. Figures 4.1 - 4.3 show the five stages required to solve this problem. Each stage (t) represents one year and at each stage, we define the states (d_t) which are the possible levels of budget that can be carried to the following years. The decision (W_t^*) at each state (d_t) is the optimum spending level. At stage (1), there is only one possible spending level at each state because, for example, if \$0 was left for the following years, then all the \$3 Million budget should be spent in this year. At the final stage, we can not carry any money after the end of the analysis period. Thus, there is only one state which is zero. Each square, either dark or blank, represents the decision $\text{Dec}(t, d_t, w_t)$ obtained from solving the Inner model for a bridge population $P(t, d_t, w_t)$. $\text{Dec}(t, d_t, w_t)$ and $P(t, d_t, w_t)$ have been defined in Section 4.2.1. The dark squares represent the optimum solution for our example. To find this optimum decision, the dynamic programming tracks the optimal sub-decisions from the last stage backward to the first one. As shown in the figures, the optimal spending at stage (5) is \$3 M/year. This corresponds to previous state (d_4^*) of (0). Going back to state (0) of stage (4), the optimal spending is to be \$3 M/year with (d_3^*) of (0). By back tracking the solution in the same way, the optimal spending levels for all the years can be found. These are \$4 M/year, \$4 M/year and \$1 M/year for years 3, 2, and 1 respectively. It should be noted that the budget increments can be taken to be any other suitable number instead of 1 million. This depends on the network size and the budget.

Year (1):

d_1	W_1				$f_1(d)$	W_1^*
	0	1	2	3		
0				□	□	1
1			□		□	
2		■			■	
3	□				□	

Figure 4.1 Demonstration for the Network Optimization Model

Year (2):

d_2	W_2							$f_2(d)$	W_2^*	$d_1^* = d_2 + W_2^* - 3$
	0	1	2	3	4	5	6			
0				☐	☐	☐	☐	☐	4	2
1			☐	☐	☒	☐		☒		
2		☐	☐	☐	☐			☐		
3	☐	☐	☐	☐				☐		
4	☐	☐	☐					☐		
5	☐	☐						☐		
6	☐							☐		

Year (3):

d_2	W_2										$f_2(d)$	W_2^*	$d_1^* = d_2 + W_2^* - 3$
	0	1	2	3	4	5	6	7	8	9			
0			☐	☒	☐	☐	☐	☐	☐	☐	☒	4	1
1		☐	☐	☐	☐	☐	☐	☐	☐		☐		
2		☐	☐	☐	☐	☐	☐	☐			☐		
3	☐	☐	☐	☐	☐	☐	☐				☐		
4	☐	☐	☐	☐	☐	☐					☐		
5	☐	☐	☐	☐	☐						☐		
6	☐	☐	☐	☐							☐		
7	☐	☐	☐								☐		
8	☐	☐									☐		
9	☐										☐		

Figure 4.2 Demonstration for the Network Optimization Model

Year (4):

d_4	W_4													$f_4(d)$	W_4^*	$d_3^* = d_4 + W_4^* - 3$
	0	1	2	3	4	5	6	7	8	9	10	11	12			
0				■	□	□	□	□	□	□	□	□	□	■	3	0
1			□	□	□	□	□	□	□	□	□	□		□		
2		□	□	□	□	□	□	□	□	□	□			□		
3	□	□	□	□	□	□	□	□	□	□				□		
4	□	□	□	□	□	□	□	□	□					□		
5	□	□	□	□	□	□	□	□						□		
6	□	□	□	□	□	□	□							□		
7	□	□	□	□	□	□								□		
8	□	□	□	□	□									□		
9	□	□	□	□										□		
10	□	□	□											□		
11	□	□												□		
12	□													□		

Year (5):

d_5	W_5													$f_5(d)$	W_5^*	$d_4^* = d_5 + W_5^* - 3$
	3	4	5	6	7	8	9	10	11	12	13	14	15			
0	■	□	□	□	□	□	□	□	□	□	□	□	□	■	3	0

Figure 4.3 Demonstration for the Network Optimization Model

4.4 Demonstration for The Inner Model

The Inner Model, as mentioned earlier, is responsible for solving the inner problems associated with each element of the outer model. Each problem has a limited budget (BD) to be allocated to (N) bridges and each bridge has many improvement alternatives, from which only one must be chosen. As discussed in Section 4.2.2, the stages will be taken as the bridges themselves. Thus, for a network of (N) bridges, there are (N) stages. The states of each stage are defined as the available budget. The first state begins from zero and then the states increase with an increment, such that the project costs will be multiples of it, until the last state equals to the limited budget (BD). A computer program, written in Pascal code and called "DPBridge", has been developed to simulate the Dynamic Programming Model. DPBridge can simulate only the Inner Model to perform a single year optimization and it also has the ability to perform multi-period optimization utilizing the D.P. Outer Model. DPBridge user manual and its Pascal code are available in Appendix II. However, a numerical example is presented below to demonstrate the technique of the Inner Model.

Example (1):

Table 4.1 shows the initial costs (IC) and benefit loss (BL) of a set of projects recommended for consideration in connection with four different hypothetical bridges. The available budget for this problem is \$18,000. It can be noticed, from Table 4.1, that the first alternative for each bridge is the "Do Nothing" alternative. This alternative always generates the maximum benefit loss but also has an initial cost of zero. The solution of the problem is to choose only one alternative for each bridge in such a way that their total initial cost is less than the available budget and their total benefit loss is minimum. Tables 4.2 to 4.5 illustrate the solution steps. It should be noted that the states and the benefit loss are in thousands of dollars. At each stage there are 19 possible budget levels using increments of \$1,000. By back tracking the solution from stage (IV) to stage (I), the optimal decision can be obtained. This includes the following projects: (IV-3), (III-2), (II-2) and (I-2) with total initial costs of \$17,000 and total benefit loss of 17,000.

Table 4.1 Data for Example (1)

Bridge	Alternative	Initial Cost	Benefit Loss
I	1	0	15,000
	2	3,000	7,000
	3	8,000	0
II	1	0	20,000
	2	2,000	10,000
	3	9,000	0
III	1	0	10,000
	2	5,000	0
	3	7,000	2,000
IV	1	0	10,000
	2	4,000	5,000
	3	7,000	0

Table 4.2 Stage (1) of Example (1)

S_i	A_i			$f_i(S_i)$	A_i^*
	1	2	3		
0	15	-	-	15	1
1	15	-	-	15	1
2	15	-	-	15	1
3	15	7	-	7	2
4	15	7	-	7	[2]
5	15	7	-	7	2
6	15	7	-	7	2
7	15	7	-	7	2
8	15	7	0	0	3
9	15	7	0	0	3
10	15	7	0	0	3
11	15	7	0	0	3
12	15	7	0	0	3
13	15	7	0	0	3
14	15	7	0	0	3
15	15	7	0	0	3
16	15	7	0	0	3
17	15	7	0	0	3
18	15	7	0	0	3

Table 4.3 Stage (II) of Example (1)

S_{II}	A_{II}			$f_{II}(S_{II})$	$S_I^* = S_{II} - IC(A_{II})$	A_{II}^*
	1	2	3			
0	35	-	-	35	0	1
1	35	-	-	35	1	1
2	35	25	-	25	0	2
3	27	25	-	25	1	2
4	27	25	-	25	2	2
5	27	17	-	17	3	2
6	27	17	-	17	<u>4</u>	[2]
7	27	17	-	17	5	2
8	20	17	-	17	6	2
9	20	17	15	15	0	3
10	20	10	15	10	8	2
11	20	10	15	10	9	2
12	20	10	7	7	3	3
13	20	10	7	7	4	3
14	20	10	7	7	5	3
15	20	10	7	7	6	3
16	20	10	7	7	7	3
17	20	10	7	7	8	3
18	20	10	7	7	9	3

Table 4.4 Stage (III) of Example (1)

S_{III}	A_{III}			$f_{III}(S_{III})$	$S_{III}^* = S_{III} - IC(A_{III})$	A_{III}^*
	1	2	3			
0	45	-	-	45	0	1
1	45	-	-	45	1	1
2	35	-	-	35	2	1
3	35	-	-	35	3	1
4	35	-	-	35	4	1
5	27	35	-	27	5	1
6	27	35	-	27	6	1
7	27	25	37	25	2	2
8	27	25	37	25	3	2
9	25	25	27	25	4/8	2/1
10	20	17	27	17	5	2
<u>>11</u>	20	17	27	17	<u>6</u>	<u>[2]</u>
12	17	17	19	17	7/12	2/1
13	17	17	19	17	8/13	2
14	17	15	19	15	9	2
15	17	10	19	10	10	2
16	17	10	17	10	11	2
17	17	7	12	7	12	2
18	17	7	12	7	13	2

Table 4.5 Stage (IV) of Example (1)

S_{IV}	A_{IV}			$f_{IV}(S_{IV})$	$S_{IV}^* = S_{IV} - IC(A_{IV})$	A_{IV}^*
	1	2	3			
18	55	20	17	17	<u>11</u>	<u>[3]</u>

4.5 Comparison of Incremental B/C Technique and D.P. Model

The comparison will be performed between using Incremental B/C ratio and using the Inner D.P. model for ranking bridge projects for a given year under a limited budget. The comparison can not be made between Incremental B/C ratio and the Outer D.P. model because the B/C ratio does not have the ability to determine the spending level for each year nor the timing for each project. The Incremental B/C ratio was chosen to represent all the ranking methods because of its superiority, as believed by most of BMS developers. Farid et al. (1994-b) have proven that the Incremental B/C technique is superior to empirical sufficiency rating methods. The Incremental B/C technique does overcome a major drawback for the sufficiency rating method, which is the inability to determine the recommended action for each bridge. But it can not provide the optimal solution for allocating a limited budget to a network of bridges. This is because it lacks the ability to optimize the system benefits.

In this section, a comparison between the Incremental B/C technique and the D.P. Inner model will be performed. Firstly, the Incremental B/C technique will be summarized. Secondly, the comparison will be presented using a hypothetical network of four bridges. The last part of this section will prove the superiority of the D.P. model to incremental B/C technique using a sample of 25 in-service bridges in North Carolina.

4.5.1 Incremental B/C Technique

The incremental B/C procedure can be summarized in the following steps (McFarland et al., 1979):

- 1) Arrange all projects in ascending order of their costs.
- 2) Calculate incremental costs and incremental benefits for moving from one project to the next for each bridge.
- 3) Calculate the incremental B/C ratio for each project and if it is less than one, skip this

project from the comparison.

- 4) Select the alternatives with the highest incremental B/C ratio at each bridge and arrange them in the order of decreasing B/C ratio.
- 5) Begin with the highest B/C ratio, then select projects until available budget is exhausted.

McFarland et al. (1983) have developed a computer program, called INCBEN, to perform the incremental B/C calculations. Another step was added to the above procedure and was called the "switching rule". In the case of some unspent budget the "switching rule" will: "drop the last accepted cost increment and select other cost increments until the excess budget is exhausted" Farid et al. (1994-a).

4.5.2 Comparison using a Hypothetical Network

In this section, the two methods will be compared using a hypothetical network of four bridges. To be compatible, the objective will be to maximize the system benefits. The steps described in the previous section will be followed to carry out the Incremental B/C calculations. Table 4.6 shows the initial costs and the net benefits for four hypothetical bridges. For simplicity, the "Do Nothing" alternatives were assumed to have initial costs and net benefits equal to zero. Table 4.7 illustrates steps 1, 2 and 3 of the incremental B/C calculations. Step 4 is to select the alternatives with the highest Incremental B/C for each bridge and then arrange them in the order of decreasing Incremental B/C ratio. Table 4.8 presents step 4. Now, we will find the problem solutions at different budget levels and compare them with the computer output of the "DPBridge".

Tables 4.9 and 4.10 show the results of the two techniques. The computer output of "DPBridge" is available in Appendix III. The results of the two approaches prove the superiority of the D.P. model to the incremental B/C technique. The two approaches recommended different alternatives at the same budget level. For any budget level between \$22,000 and 24,000, the use of the D.P. model will result in a net benefit of \$60,000, while

2

PM-1 3½" x 4" PHOTOGRAPHIC MICROCOPY TARGET
NBS 1010a ANSI/ISO #2 EQUIVALENT

PRECISIONSM RESOLUTION TARGETS

Table 4.6 Data for the Four Hypothetical Bridges

Bridge	Alternative	Initial Cost	Net Benefit
I	1	0	0
	2	6,000	23,000
	3	12,000	40,000
II	1	0	0
	2	3,000	3,000
	3	20,000	30,000
III	1	0	0
	2	10,000	20,000
	3	15,000	25,000
IV	1	0	0
	2	6,000	10,000
	3	24,000	40,000

Table 4.7 Steps 1,2 & 3 of the Incremental B/C Calculations

Alternative	Cost	Benefit	ΔC	ΔB	$\Delta B / \Delta C$
I-2	6,000	23,000	6,000	23,000	3.83
I-3	12,000	40,000	6,000	17,000	2.83
II-2	3,000	3,000	3,000	3,000	1.00
II-3	20,000	30,000	17,000	29,000	1.71
III-2	10,000	20,000	10,000	20,000	2.00
III-3	15,000	25,000	5,000	5,000	1.00
IV-2	6,000	10,000	6,000	10,000	1.67
IV-3	26,000	40,000	20,000	30,000	1.50

Table 4.8 Step 4 of the Incremental B/C Calculations

Bridge	Alternative	$\Delta B / \Delta C$	Initial Cost	Net Benefit
I	2	3.83	6,000	23,000
III	2	2	10,000	20,000
II	3	1.71	20,000	30,000
IV	2	1.67	6,000	10,000

Table 4.9 Results of the Two Techniques for Budgets of \$22,000-\$24,0000

Comparison Parameter	Incremental B/C	D.P. Model
Recommended Alternatives	(I-2), (II-1), (III-2)& (IV-2)	(I-3), (II-1), (III-2)& (IV-1)
Used Budget	\$22,000	\$22,000
Net Benefit	\$53,000	\$60,000

Table 4.10 Results of the Two Techniques for a Budget of \$25,000

Comparison Parameter	Incremental B/C	D.P. Model
Recommended Alternatives	(I-2), (II-2), (III-2)& (IV-2)	(I-3), (II-2), (III-2)& (IV-1)
Used Budget	\$25,000	\$25,000
Net Benefit	\$56,000	\$63,000

the use of the Incremental B/C technique will gain only \$53,000. At a budget level of \$25,000, the use of the D.P. model will result in an increase of \$7,000 in the net benefit gained. Even by applying the "switching rule" of INCBEN, it failed to enhance the results of the Incremental B/C technique. For example; for bridge I, it will try to replace alternative 2 by alternative 3, but in this case the total costs will exceed the granted budget. Thus, alternative 2 will stay in the selected group. The same trial will be attempted for bridge IV, but alternative 3 can not replace alternative 2 because of its high initial cost.

The hypothetical example presented above shows how the Incremental B/C technique fails to find the optimal solution even for a very small network of four bridges. For large networks, the benefit gained by using the D.P. model will be much higher. This will be demonstrated in the next section.

4.5.3 Comparison Using 25 In-Service Bridges in North Carolina

Farid et al. (1994-b) have performed a comparison between Incremental B/C technique, using INCBEN, and the sufficiency rating method to allocate limited budgets to 25 in-service bridges in North Carolina. This study proved the superiority of INCBEN to the sufficiency rating method. Figure 4.4 shows the net benefits gained by repairing 25 bridges in North Carolina, when allocating different levels of fund using two methods; the incremental B/C method and the sufficiency rating method. The sufficiency rating method recommends replacement unless the initial cost of rehabilitation is less than 50 percent of the replacement cost. The figure demonstrates the superiority of the incremental B/C method. However, the data used for this study were used herein to compare between the Incremental B/C technique and the D.P. Inner Model. Table 4.11 shows the data for the 25 bridges. The Net Benefits represent the agency and the user benefits added together. Table 4.12 illustrates INCBEN results for 11 different levels of funds. At each fund level, the table shows the net benefits gained by carrying out the recommended alternatives, and the excess budget that has not been used. The results of the D.P. Inner model are displayed in Table 4.13.

Figure 4.4 Comparison of the Net Benefits Gained by INCBEN and Sufficiency Rating
(Source: Farid et al., 1994-b)

Table 4.11 Costs and Benefits for All Bridge Improvement Alternatives in \$1,000
(Source: Farid et al., 1994-b)

Bridge	N.C. Code	Alternative	Alternative No.	Initial Cost	Net Benefits
1	00210	D	0	0	0
		M	1	165	662
		R	2	742	1899
		N	3	895	1857
2	05125	D	0	0	0
		M	1	2	-214
		R	2	40	170
		N	3	283	364
3	08052	D	0	0	0
		M	1	4	544
		N	2	520	385
4	10381	D	0	0	0
		M	1	429	1274
		R	2	1550	-5434
		N	3	2650	6618
5	17001	D	0	0	0
		M	1	70	1530
		R	2	725	-1
		N	3	1400	160
6	29058	D	0	0	0
		M	1	7	365
		R	2	627	304
		N	3	548	452
7	45009	D	0	0	0
		R	1	6	1741
		M	2	28	16536
		N	3	3755	15407
8	58016	D	0	0	0
		r	1	102	178
		R	2	289	106
		N	3	304	1559
9	58030	D	0	0	0
		r	1	121	229
		R	2	349	262
		N	3	36666	267

a: D stands for do nothing, M for maintenance, R or r for rehabilitation, N for new bridge and C for closure

Table 4.11 Costs and Benefits for All Bridge Improvement Alternatives in \$1,000
(Continued)
(Source: Farid et al.,1994-b)

Bridge	N.C. Code	Alternative ^a	Alternative No.	Initial Cost	Net Benefits
10	58032	D	0	0	0
		r	1	168	195
		R	2	247	141
		N	3	392	32
11	58033	D	0	0	0
		r	1	209	428
		R	2	712	-14
		N	3	682	1181
12	58089	D	0	0	0
		r	1	129	257
		R	2	370	168
		N	3	388	165
13	58091	D	0	0	0
		r	1	129	242
		R	2	370	156
		N	3	388	167
14	59100	D	0	0	0
		r	1	163	301
		R	2	462	195
		N	3	485	207
15	58102	D	0	0	0
		r	1	173	332
		R	2	496	198
		N	3	521	209
16	58128	D	0	0	0
		r	1	202	260
		R	2	297	288
		N	3	471	131
17	61010	D	0	0	0
		M	1	3	111
		R	2	86	192
		N	3	145	167

a: D stands for do nothing, M for maintenance, R or r for rehabilitation, N for new bridge and C for closure

Table 4.11 Costs and Benefits for All Bridge Improvement Alternatives in \$1,000
(Continued)
(Source: Farid et al., 1994-b)

Bridge	N.C. Code	Alternative ^a	Alternative No.	Initial Cost	Net Benefits
18	73411	D	0	0	0
		M	1	17	2156
		R	2	86	2581
		N	3	3600	2143
19	75171	D	0	0	0
		M	1	4	146
		R	2	116	2069
		N	3	444	2105
20	80173	D	0	0	0
		M	1	1	79
		R	2	4	75
		N	3	115	4
21	84007	D	0	0	0
		M	1	1	52
		r	2	40	137
		R	3	50	138
		N	4	80	127
22	84133	D	0	0	0
		C	1	0	583
		R	2	53	27
		N	3	516	173
23	89034	D	0	0	0
		M	1	9	241
		R	2	72	452
		N	3	319	326
24	91014	D	0	0	0
		M	1	1	274
		R	2	455	19
		N	3	410	201
25	97060	D	0	0	0
		M	1	5	360
		R	2	300	284
		N	3	560	524

a: D stands for do nothing, M for maintenance, R or r for rehabilitation, N for new bridge and C for closure

Table 4.12 Results of INCBEN
(Source: Farid et al., 1994-b)

Budget (\$1,000)	Net Benefits (\$)	Excess Budget (\$1000)
250	8,402	1
500	9,167	34
1,000	10,595	28
2,120	12,317	0
2,142	27,112	0
2,180	27,496	0
2,249	27,921	0
3,000	31,796	9
4,000	33,621	97
5,000	36,947	21
8,036	39,493	0

Table 4.13 Results of the D.P. Model

Budget (\$1,000)	Net Benefits (\$)	Excess Budget (\$1000)
250	24,539	0
500	25,978	4
1,000	28,021	0
2,120	30,857	2
2,142	30,857	24
2,180	30,943	13
2,249	31,114	2
3,000	32,385	35
4,000	35,382	16
5,000	37,419	18
8,036	39,493	0

The "DPBridge" computer program was used to perform the analysis. The computer output was too large to be included in the appendices, but it is available in computer files. The alternatives selected by the two methods are shown in Tables 4.14 and 4.15. The two techniques have selected different alternatives for the 25 bridges. The most important aspect is the "Net Benefits" gained by carrying out these alternatives.

The "Net Benefits" gained by using the two methods were plotted, in Figure 4.5, for the 11 levels of fund. The figure demonstrates how the D.P. model generates more benefits than the Incremental B/C technique for all levels of fund except for the last level. At the highest level of fund, which is \$8,036,000, the two methods had the same results. The incremental B/C method succeeded to get the optimal solution only when the budget was unlimited or enough to carry out the best economical alternative for each bridge. But when the budget was limited, and this is the case for most of the transportation agencies, it failed to get the optimal solution. On the other hand, the D.P. model always can get the optimal solution. The benefits of using the D.P. model can be recognized greatly at the low levels of fund, which is the case for most of the transportation agencies. At budgets of \$250,000, \$500,000 and \$1 million, the D.P. model generates net benefits equal to three times the net benefits gained by the Incremental B/C technique. Figure 4.5 shows how the net benefits gained by the Incremental B/C method jumps to twice its magnitude for a slight change of the fund level from \$2,120,000 to \$2,142,000. This indicates the inconsistency of the Incremental B/C method and how it can be led astray by some kinds of improvement alternatives. On the other hand, one can notice, from Figure 4.6, the consistency of the behaviour of the D.P. model.

For large networks, the Incremental B/C technique will not be able to find the optimal solution, or even a solution near the optima, and the benefits lost because of its decision will be much higher. This is simply because the Incremental B/C method is not an optimization technique. The use of the D.P. model will result in the optimum allocation for the available budget and the maximum possible benefits will be gained. The "DPBridge" program was developed with the ability to handle any number of bridges. It runs on any 386 or 486

Figure 4.5 Comparison of the Net Benefits Gained by INCBEN and D.P. Model

Personal Computer with a minimum RAM of 2 Meg. Bytes. The most important is the hard disk space, as it requires $(0.015 \times N \times B)$ Meg. Bytes of hard disk space, where (N) is the number of bridges and (B) is the available budget in million of dollars.

4.6 Importance of the Outer Model

The results presented in the previous section have shown the superiority of the D.P. Inner model to the Incremental B/C method. Subsequently, one may ask what is the importance of the D.P. Outer model as long as the Inner model can find the optimal solution. The Inner model can indeed find the optimal solution for a given year under a limited budget. However, this is only part of the overall problem. We have to find the optimum timing for each bridge to be repaired and also the optimum spending for each year of the analysis period. This is the function of the Outer model.

Table 4.13 illustrates the results of the Inner model for 11 different spending levels. If North Carolina DOT can spend \$8 million this year to repair the 25 bridges, is it the optimal spending level when considering an analysis period of 5 or 10 years? Although this level of spending will result in the highest net benefits gained for this year, one can not answer that question unless he examines all the possible combinations of spending over the analysis period. It can be noticed from Table 4.13 that the net benefits for a budget of \$4 million was \$35,382 and it was \$39,493 for a budget of about \$8 million. This means that 90 percent of the benefits can be achieved by spending only half of the \$8 million. Thus, the Inner model by itself can not provide the optimal spending level for each year of the analysis period nor the optimal timing for each bridge to be repaired.

4.7 Application of the Outer Model

The input of the Outer model requires information about all the possible alternatives for all bridges with the associated life cycle costs and user costs if a bridge is to be repaired at any year of the analysis period. Unfortunately, this kind of data are not readily available in any transportation agency. The Ministry of Transportation of Ontario and the Regional Municipality of Ottawa-Carleton were consulted regarding these data but neither one could provide them. Subsequently, the application of the Outer model will be illustrated using a hypothetical network of bridges.

A hypothetical data for a network of 50 bridges were constructed. Appendix IV contains the input file for the first year of the analysis period, which is assumed in this particular case to be 5 years. This file contains all the possible improvement alternatives for the 50 bridges associated with their initial costs and benefit losses. To perform multi-period optimization, DPBridge requires one separate file for each year of the analysis period. The required files were generated from the first year's data using the following assumptions:

- 1) The initial costs are constants in real dollars and will be converted to present worth values using a real rate of return (R).
- 2) The budget given for each year is in present worth value.
- 3) The benefit losses will be increased every year by a constant percent (BLR).

Ten different sets of data were generated using different values for (R) and (BLR). The first five data sets, group 1, were generated using a constant interest rate of 5 % and five different values for BLR. The rest of the data sets, group 2, were generated using a constant BLR of 10 % and five different values for the interest rate. Tables 4.16 and 4.17 illustrate the results obtained by DPBridge using data sets of group 1 and group 2, respectively. The third column, in the two tables, shows the budget available for the analysis period expressed as million of dollars per year. The last column displays the budget distribution recommended by DPBridge. The alternatives selected for each year were not listed in the table. However,

Table 4.16 Results of the Outer Model Application (Group 1)

Data Set	R	BLR	Available Budget (\$M/year)	DPBridge Results: Budget Distribution
1	5 %	5 %	2	2 - 0 - 0 - 0 - 8
			1	1 - 1 - 1 - 0 - 2
2	5 %	10 %	2	2 - 2 - 0 - 0 - 6
			1	1 - 1 - 1 - 0 - 2
3	5 %	15 %	2	2 - 2 - 0 - 0 - 6
			1	1 - 1 - 1 - 0 - 2
4	5 %	20 %	2	2 - 2 - 2 - 0 - 4
			1	1 - 1 - 1 - 1 - 1
5	5 %	25 %	2	2 - 2 - 2 - 0 - 4
			1	1 - 1 - 1 - 0 - 2

Table 4.17 Results of the Outer Model Application (Group 2)

Data Set	R	BLR	Available Budget (\$M/year)	DPBridge Results: Budget Distribution
6	0 %	10 %	2	2 - 1 - 3 - 0 - 4
			1	1 - 1 - 1 - 1 - 1
7	5 %	10 %	2	2 - 2 - 0 - 0 - 6
			1	1 - 1 - 1 - 0 - 2
8	8 %	10 %	2	2 - 2 - 0 - 1 - 5
			1	1 - 1 - 1 - 0 - 2
9	10 %	10 %	2	2 - 0 - 0 - 0 - 8
			1	1 - 1 - 1 - 0 - 2
10	15 %	10 %	2	2 - 0 - 0 - 0 - 8
			1	1 - 1 - 1 - 0 - 2

as an example, the complete output of DPBridge for the third line and the fifth line of Table 4.16 are given in Appendix IV. The budget distribution column shows the budget that is to be allocated for each year of the analysis period, from year 1 to year 5. For example, the first line of the Table 4.16 recommends spending \$2 M in the first year, and \$8 M in the fifth year and nothing is allocated for the other years.

Bridge deterioration rate was expressed by the BLR percent introduced earlier. BLR is the rate of increase in the benefit loss, which increases when the bridge deterioration rate increases. From Table 4.16, it can be concluded that early allocation to the available funds is recommended when having a high bridge deterioration rate. This can be noticed by comparing the recommended budget distribution for the five sets at a fund level of \$2 M/year. DPBridge recommended to spend \$ 8M in the fifth year and \$ 2M in the first year at a BLR of 5 %. When BLR increased to 10 % or 15 %, it was recommended to decrease the spending level of the fifth year from \$ 8M to \$ 6M and to spend the \$ 2M difference in the second year. For high deterioration rates represented by of BLR of 20 % and 25 %, early budget allocation was recommended and the budget distribution was to spend \$ 2M in each of the first three years and \$ 4M in the fifth year. Although the budget distribution was recommended to be the same for set 2 and set 3, the recommended alternatives for the two cases were different. This can be noticed from the DPBridge output files which are given in Appendix IV. For a fund level of \$ 1M/year, the budget distribution were the same for four cases of the five cases presented in Table 4.16. However, the recommended alternatives for the four cases were completely different.

When comparing the results of Table 4.17, one can notice that the recommended budget distribution at a fund level of \$ 2 M/year were different for the five cases presented except for set 10, which has the same budget distribution recommended for set 9. Although data set 10 and data set 9 have the same budget distribution, they do not have the same recommended bridge alternatives. For a one million per year fund level, the recommended budget distribution for all of the sets were the same except for set 6. Despite Data sets 7 to 10 have the same budget distribution at a fund level of \$ 1 M/year, DPBridge recommended

different bridge alternatives for each data set.

The results illustrated in Tables 4.16 and 4.17 show how DPBridge can perform multi-period optimization to allocate limited budget to a network of 50 bridges. The results indicate how setting priorities to bridge projects is affected by the interest rate and the deterioration rate of bridges.

4.8 Summary

After reviewing the available methods for allocating funds to bridge rehabilitation and replacement projects, it is believed that there is an urgent need for a model that can utilize the available resources in the most efficient and cost effective way. The available methods can not perform multi-period optimization and even for a single year allocation, the optimal solution can not be reached. Thus, in this chapter, a multi-period optimization model was developed. The model consists of two combined models, the Outer Model and the Inner Model, and utilizes the dynamic programming technique to formulate both of them. The function of the model is to allocate limited budget to bridge R&R projects and to determine the optimum timing for implementation. The Inner Model performs single year optimization, while the Outer model optimizes the system benefits over time. In allocating the budget, the model objective is to minimize what has been defined as the system benefit loss. Equation 3.6 defines the benefit loss associated with carrying out bridge improvement alternatives.

A computer software, called "DPBridge", was developed to simulate the developed network optimization model. DPBridge can perform single year optimization as well as multi-period optimization.

For single year optimization, the Inner Model was compared to the incremental benefit/cost method, which is the most widely used method, using 25 in-service bridges in

North Carolina. The comparison proved the superiority of the D.P. Inner Model to the incremental benefit/cost method. The function of the Outer Model can not be performed by any of the existing methods. The function of the Outer Model was demonstrated using a hypothetical network of 50 bridges, due to lack of real data. The application of the Outer Model showed how it is important to consider all the analysis period when setting priorities to bridge projects. The application indicated also that the budget allocation process is affected by the interest rate and the bridge deterioration rates.

As part of the research conducted to develop a priority setting scheme for bridge R&R projects, Artificial Neural Network (A.N.N) approach was utilized to develop a single year optimization model. The findings of this part of the research is presented in the next chapter. The developed neural network method will be compared to the D.P. Inner Model and the best technique will be selected.

CHAPTER 5

UTILIZATION OF NEURAL NETWORKS IN THE NETWORK OPTIMIZATION MODEL

5.1 Background

The main objective of this chapter is to present a technique using the Artificial Neural Network (A.N.N.) method to solve the Inner model described in Chapter 4. As discussed earlier, the Inner model has to be solved for every element of the Outer model, and this requires an efficient technique to be employed. From the operations researcher's point of view, artificial neural networks are algorithms with certain characteristics that may be able to solve certain optimization tasks. The expected advantages of using A.N.N. include improvement in speed of operation by parallel implementation either in hardware or in software. Hence neural networks can perform well even in conventional computers. At the end of this chapter a comparison between the performance of the the D.P. Inner model and the A.N.N. model will be presented and the best technique will be selected.

It is important to understand the steps leading to the formulation of the final model which utilizes A.N.N. in BMS. Therefore, the steps associated with the development of preliminary and final A.N.N. model will be discussed in this chapter.

An artificial neural network takes after its biological twin through its composition of nodes and the connections among the nodes. The human central nervous system consists of about five to ten hundred billion nerve cells or neurons. The major structures of a typical nerve cell include dendrites, the cell body, and a single axon. The connections between the neurons are called synapses and each neuron is connected to a large number of other neurons.

The neuron decision or its activation is due to chemical reactions inside the cell body. A neuron will receive nerve impulses from other neurons through the synapses. These impulses can be either excitatory (decreasing the polarization of the cell) or inhibitory (increasing the polarization of the cell). Then, they will be summed at the axon of the cell and according to the amount of depolarization, the neuron can be activated, (Freeman and Skapura, 1991). This means that the neuron has only two states; activated (on) or not-activated (off). The output of this neuron will be sent to other neurons as well. Figure 5.1 illustrates several basic neural circuits that are found in the human nervous system. Each neuron receives and sends impulses from and to many other neurons. The feedback path is shown clearly in circuit (c).

The first attempt to simulate neural networks was made by McCulloch and Pitts (1943). The basic idea of artificial neural networks is to construct a network of cells which are called artificial neurons, nodes, units or processing elements (PE). The synapses are simulated by weighted connection. Figure 5.2 shows the structure of a single PE in a neural network. The i th PE receives input (X_j) from the j th PE. The arrows in Figure 5.2 represent the input connection from other PEs. The weight of each connection (T_{ij}) is analogous to the strength of the synaptic connection between neurons. The PE has only a single output which can be input to many other PEs. The net input to the i th PE can be written as follows (Freeman and Skapura, 1991):

$$\text{Input}_i = \sum_j X_j * T_{ij} \quad (5.1)$$

After estimating the net input, it will be converted to an activation value $\text{Act}_i(t)$ which is, (Freeman and Skapura, 1991):

$$\text{Act}_i(t) = F_i (\text{Act}_i(t-1), \text{Input}_i(t)) \quad (5.2)$$

Eqn(5.2) describes the activation value as a function of the net input and also it may depend on the previous value of activation $\text{Act}_i(t-1)$. By applying the output function to the activation value, the output (X_i) of the artificial neuron (i) can be obtained (Freeman and Skapura, 1991):

Figure 5.1 Human Neural Circuits
(Source: Freeman and Skapura, 1991)

Figure 5.2 Structure of a Single Processing Element
(Source: Freeman and Skapura, 1991)

$$X_i = f_i (Act_i) \quad (5.3)$$

There are several types of neural networks. Each type has different architecture, activation function, output function, and weighted connections. This depends on the function of human brain that the A.N.N. aims to simulate. Such functions include but are not limited to the following (Burk and Ignizio, 1992):

- Prediction and estimation.
- Pattern recognition.
- Clustering.
- Optimization.

Artificial neural networks can be grouped into two categories; adaptive or feedforward neural networks and non-adaptive or recurrent neural networks. The first one needs a training set of data to adapt or adjust its connection weights, then the weights obtained at the convergence will be used to perform the intended function. The impulses go only in a unidirectional fashion. The common networks of this group include the backpropagation network and the radial basis function. Non-adaptive networks do not need the training phase, but the initial weights are, used and at the convergence, the states of the neurons will represent the problem solution. This group of networks exhibit dynamic behaviours and feedback is allowed. Recurrent neural networks can be deterministic, e.g. Hopfield Network, or stochastic e.g. the Boltzmann Machines. The main difference between the two kinds is the activation process which is based in the first on functions of real-values and in the second on probability distribution functions.

5.2 Developed Neural Network

The common approach to construct optimization neural networks is to formulate the

problem in term of minimizing a cost or "energy" function. This approach is known as the Hopfield network (Hopfield and Tank, 1985). A modified Hopfield network will be used to construct the proposed A.N.N. Two main steps should be followed in mapping an optimization problem onto a neural network which uses an energy function (Ramanujam and Sadayappan, 1988):

- 1) Choose a network architecture which decodes the outputs of the neurons into a solution to the problem.
- 2) Formulate an energy function which generates the best solutions when having a minimum value.

Energy functions resemble penalty functions in operation research. The objective function and the problem constraints will be included in the energy function as follows (Looi, 1992):

$$E = \sum_i v_i (\text{violation of constraint } i) + u (\text{"cost"}) \quad (5.4)$$

Where:

E = energy function;

v_i, u = energy function parameters, always > 0 ; and

"cost" = an optimization cost function which depends on the problem.

The objective function of the bridge problem and its constraints will be formulated as follows:

$$\text{Minimize } Z = \sum_{B=1}^N \sum_{A=0}^{M(B)} BL(B, A) * X(B, A) \quad (5.5)$$

Subject To:

$$\sum_{B=1}^N \sum_{A=0}^{M(B)} IC(B, A) * X(B, A) \leq W \quad (5.6)$$

$$\sum_{A=0}^{m(B)} X(B,A) = 1 \quad \text{for all } B \quad (5.7)$$

$$X(B,A) = 1, 0 \quad (5.8)$$

Where:

- $Z =$ the benefit loss for any stage (t) at any state (d_t) of the Outer model, when spending level or available budget equals W \$/year;
- $N =$ total number of bridges;
- $m(B) =$ number of improvement alternatives for bridge (B);
- $BL(B,A) =$ the loss in system benefits if alternative (A) was chosen for bridge (B);
- $X(B,A) =$ 1 if alternative (A) was chosen for bridge (B) and 0 otherwise; and
- $W =$ the available budget (\$/year).

5.2.1 Preliminary Formulation

The A.N.N. developed here is basically a Hopfield network. The energy function was derived using an approach presented by Lee and Hsu (1989). The network as illustrated in Figure 5.3 consists of one layer of neurons. This means that computations of each neuron can be done parallel with other neurons, and the model can be easily mapped to parallel architecture. If there are (N) bridges and (m) improvement alternative for each bridge, there will be (N x m) decision variables, this will require a network of (N x m) neurons. It should be noted that the "DO Nothing" alternative is included in the (m) alternatives.

Let $N \times m = n$

and $X(B,A) = X_i$

where:

$n =$ total number of neurons; and

$i =$ an integer ranging from 1 to n, which refers to alternative (A) of bridge (B).

where:

Figure 5.3 Architecture of the Preliminary Network

$$i = (B-1) * m + A \quad (5.9)$$

Figure 5.3 shows that each neuron will receive four inputs and these are: feedback input from itself, input from all other neurons, input from neurons representing alternatives for the same bridge and the benefit loss due to the alternative which the neuron represents. Costs of improvement alternatives will represent the weights of the neuron connections.

Energy Function:

The energy function should be derived so that the lowest energy states correspond to the best solutions; i.e. the minimum loss in the system benefits. The first term will ensure this requirement as follows:

$$E_1 = \sum_{i=1}^N BL_i * X_i - \sum_{i=1}^N BL_i \quad (5.10)$$

The term E_1 is equal to $(-BL_i)$ if all X_i are equal to zero, or otherwise it is greater. This will guarantee the lowest value of (E) while getting the minimum benefit loss.

The budget constraint represented by Eqn(5.6) will be mapped to the following term E_2 :

$$E_2 = F_1 \left(\left[\sum_{i=1}^N IC_i * X_i \right] - W \right) \quad (5.11)$$

Where:

$$F_1(z) = 0 \quad \text{if } z \leq 0$$

$$F_1(z) = z^2/2 \quad \text{if } z > 0$$

This will force the energy term to have its lowest values when the constraint is satisfied, while having larger values if the constraint is violated more.

Equation (5.7) represents (N) constraints which ensure that at least one alternative will be chosen for each bridge. This will be transformed to the following energy term:

$$E_3 = \sum_{i=1}^n F_2 \left(\left[\sum_{j=n(B-1)+1}^m x_j \right] - 1 \right) \quad (5.12)$$

Where:

$$F_2(z) = 0 \quad \text{if } z = 0$$

$$F_2(z) = z^2/2 \quad \text{if } z \neq 0$$

The last term of the energy function is defined to ensure that the decision variables will have values of 1 or 0. Figure 5.4 shows two appropriate functions and their corresponding graphs, which can enforce the zero/one property. The following equation will be used for this purpose (Lee and Hsu, 1989):

$$E_4 = \sum_{j=1}^n (x_j^4 - 2x_j^3 + x_j^2) \quad (5.13)$$

Now the energy function (E) can be written as follows:

$$E = a * E_1 + b * E_2 + c * E_3 + d * E_4 \quad (5.14)$$

Where a, b, c, and d are non-negative constants which reflect the importance of each term.

The net input of each neuron is estimated by the change of the energy function due to the change in the state of this neuron (Lee and Hsu, 1989):

$$Input_i(t) = - \partial E / \partial x_i(t-1) \quad (5.15)$$

$$Input_i(t) = (a / BL_i) - b * IC_i * f_1 \left(\left[\sum_{j=1}^n IC_j * x_j(t-1) \right] - W \right)$$

$$- c * f_2 \left(\left[\sum_{j=n(B-1)+1}^m x_j(t-1) \right] - 1 \right)$$

$$- d * (4x_i^3(t-1) - 6x_i^2(t-1) + 2x_i(t-1)) \quad (5.16)$$

$$\sum_{i=1}^n X_i = (1 - X_i) \quad 0 \leq X_i \leq 1$$

$$\sum_{i=1}^n (X_i^4 - 2 \cdot X_i^3 + X_i^2) \quad X_i \in \mathbb{R}$$

Figure 5.4 Functions Used to Enforce the Zero/One Property
(Source: Lee and Hsu, 1989)

Where:

$\text{Input}_i(t)$ = the net input of the neuron (i) at state (t);

$X_i(t-1)$ = the output of the neuron (i) at state (t-1); and

$$f_1(z) = \partial F_1(z) / \partial z$$

$$f_2(z) = \partial F_2(z) / \partial z$$

$$f_1(z) = 0 \quad \text{if } z \leq 0$$

$$f_1(z) = z \quad \text{if } z > 0$$

$$f_2(z) = 0 \quad \text{if } z = 0$$

$$f_2(z) = |z| \quad \text{if } z \neq 0$$

The activation function $\text{Act}_i(t)$ will be taken as the following deterministic sigmoid function (Freeman and Skapura, 1991):

$$\text{Act}_i(t) = \frac{1}{1 + e^{-\text{Input}_i(t) / q}} \quad (5.17)$$

Where:

q = positive scaling parameter.

By applying the output function $X_i(t)$ to the activated value, the state or the output of the neuron can be updated as follows:

$$X_i(t) = 0 \quad \text{if } \text{Act}_i(t) \leq \varepsilon \quad (5.18)$$

$$X_i(t) = 1 \quad \text{if } \text{Act}_i(t) \geq (1-\varepsilon) \quad (5.19)$$

$$X_i(t) = \text{Act}_i(t) \quad \text{otherwise} \quad (5.20)$$

Where:

ε = permissible error, which can be set between 0.01 and 0.1.

The initial states of all neurons will be set to zero. The network will be supplied by the benefit loss (BL) and cost (IC) of each alternative for all bridges, and the available budget (W). Each neuron will begin to send impulses to other neurons through synapses or connections until the network reaches a stable state. A stable state means that each neuron is either on or off, in other words the output (X_i) of all neurons are either one or zero. One means that the particular alternative is to be carried out, while zero corresponds to cancelling that alternative. If a bridge is going to receive no improvement, the "Do Nothing" alternative will be on.

By testing the described network it failed to converge when used for more than one bridge. Two major weaknesses for this network were identified. First, the penalty parameters are constants and determination of suitable values for them requires extensive experimentation. Second, the fourth term of the energy function (E_4) which was imposed to ensure the zero/one property led to a complicated energy function which got trapped in local minima. Consequently, another energy function was developed in order to avoid those drawbacks.

5.2.2 The Final Network

The Artificial Neural Network developed here is basically a version of the Hopfield network, but with a dynamic penalty parameter. The approach used to map this kind of networks was presented by Wang and Chankong (1992). This approach depends greatly on the Lagrange Multiplier method. The energy function is represented by the following equation (Wang and Chankong, 1992):

$$E = Z - L (g (x)) \quad (5.21)$$

Where Z and $g (x)$ will be generated from objective and constraints of the bridge problem and L is a penalty parameter.

$$Z = \sum_{i=1}^n BL_i * X_i \quad (5.22)$$

$$g(x) = \frac{1}{2} \left(\left(\sum_{i=1}^{n+1} IC_i * X_i \right) - W \right)^2 + \frac{1}{2} \left(\sum_{j=1}^n \left(\left(\sum_{i=n(j-1)+1}^{n*j} X_i \right) - 1 \right)^2 \right) \quad (5.23)$$

It should be noted that (Z) is the original objective function introduced by eqn(5.5). The first term of the penalty function $g(x)$ represents the budget constraint, while the second term represents the constraints of eqn(5.7), which ensure that for every bridge only one alternative will be selected. A slack variable $X(n+1)$ has been introduced to convert the budget inequality constraint to an equality constraint.

The penalty parameter (L) will be allowed to decrease by an amount (ΔL), which is inversely proportional to violation of constraints:

$$\Delta L(t) = 1 / g(x(t)) \quad (5.24)$$

$$L(t+1) = L(t) - (\Delta t * \Delta L(t)) \quad (5.25)$$

Where:

Δt = step size (0.001 - 1.0); and

$L(0)$ = initial penalty parameter (0.0001 - 1.0).

The net input of each neuron will be changed by an amount equal to the change of the energy function due to changing the state of this neuron divided by (ΔL). The division by (ΔL) will change the net input by an amount which is proportional to violation of constraints. The net input for each neuron will be estimated using the following equation (Wang and Chankong, 1992):

$$\text{Input}_i(t+1) = \text{Input}_i(t) - \Delta t * \left(\frac{\partial E}{\partial X_i} / \frac{\Delta L(t)}{a} \right) \quad (5.26)$$

This is a general equation, but the derivative of E was generated from our bridge problem:

$$\frac{\partial E}{\partial X_i} = BL_i - L [IC_i * ((\sum_{j=1}^n IC_j * X_j) + X_{n+1} - W) + \sum_{j=1}^n X_j - W] \quad (5.27)$$

for $i = 1$ to n

$$\frac{\partial E}{\partial X_{n+1}} = -L [(\sum_{i=1}^{n+1} IC_i * X_i) - W] \quad (5.28)$$

$a =$ adjusting parameter (10 - 100); and
 Input (0) = initial states are assumed to be zero.

The activation function will be the same deterministic sigmoid function represented by eqn(5.17). This function will ensure the zero/one property of the bridge problem. By applying the output function $X_i(t)$, represented by eqns(5.18 - 5.20), the state or the output of the neurons can be updated.

Figure 5.5 shows the network architecture. The network consists of two layers. First one has two neurons corresponding to (L) and (ΔL). The second layer has (n+1) massively connected neurons where the alternative costs (IC) represent the connection weights. The initial states of all neurons will be set to zero. The network will reach a stable state when all neurons of the second layer are either on or off.

5.3 Application of the Developed Networks

In this section, the Artificial Neural Networks developed in Section 5.2 will be tested

Figure 5.5 Architecture of the Final Network

using hypothetical data. A network simulator was constructed using Turbo Pascal. Two programs have been developed; one for the preliminary developed network and the second for the final network. The code of the two programs is available in Appendix V. The performance of the simulated network will be demonstrated through some examples.

5.3.1 Preliminary Developed Network

The selection of energy function's parameters has significant influence on the network convergence. Each parameter reflects the relative importance of its term. The determination of these parameters requires extensive experimentation and is the main weakness of this network. The network has been tested through numerical examples using the developed simulator. Hypothetical data have been used for this purpose.

Example (1):

One bridge was assumed to have three improvement alternatives with a limited budget of \$150,000. The benefit losses and initial costs are available in Table 5.1. The optimal solution for this problem is to choose the second alternative with an objective function equal to 100,000. This means that at a stable state the second neuron will be on while the others will be off. After extensive experimentation, the network was able to find the optimal solution but it failed to remain in this state. Figure 5.6 shows the behaviour of the objective function (Z) during iteration. It can be seen that (Z) had the value of 100,000, which is the optimal value, but it always slips to unstable state. The parameters values were as follows: $a = 25$, $b = 1.6$, $c = 12$ and $d = 10$.

Example (2):

In this example, the network was fed by data about two bridges and each bridge had two improvement alternatives. The available budget was \$800,000 and the benefit losses and initial costs are illustrated in Table 5.2. The optimal solution requires the two alternatives (1-2) and (2-1) to be carried out. Unfortunately, the network was not able to find the optima

Table 5.1 Data for Example (1)

Bridge	Alternative	Benefit Loss	Initial Costs	Solution
1	1	500,000	500,000	0
	2	100,000	100,000	1
	3	1000,000	1000,000	0

Table 5.2 Data for Example (2)

Bridge	Alternative	Benefit Loss	Initial Costs	Solution
1	1	200,000	600,000	0
	2	500,000	300,000	1
2	1	300,000	500,000	1
	2	700,000	200,000	0

Figure 5.6 Objective Function Behaviour During Iteration in Example (1)

Figure 5.7 Objective Function Behaviour During Iteration in Example (2)

at all and no stable state was reached. Figure 5.7 shows the divergent patterns of the objective function (Z).

5.3.2 The Final Network

This network was developed as explained in Section 5.2.2 to overcome the drawbacks of the previous network. The fourth term of the energy function of the previous network, which enforces the zero/one property, was omitted because its function can be realized through the activation function. It is believed that this term adds complexity to the previous network. The use of dynamic parameters for the energy function of this network has enhanced the convergence patterns greatly. The performance of this network will be demonstrated using two examples.

Example (3):

In this example, the network was fed by data about two bridges and each bridge had two improvement alternatives. The available budget was \$800,000 and the benefit losses and initial costs are as given in Table 5.2, which are the same data as used in example (2). Figures 5.8 and 5.9 illustrate the convergent patterns of the objective function (Z) and the penalty function ($g(x)$) respectively. The optimal solution for this problem is to carry out alternatives (1-2) and (2-1) with a minimum (Z) of \$800,000. It can be seen from Figure 5.8 that after 100 iterations the network reached the optimum but it later diverged for about 300 iterations before reaching its stable state. From Figure 5.9 it can be noticed that between the 100 and the 400 iterations the constraints were violated, as $g(x)$ values were greater than zero. After 400 iterations, the network converged and all neurons reached stable states; one for (1-2) and (2-1) and zero for the others. The network selected the best alternatives, satisfied the budget constraints and had only one neuron "on" for each bridge.

Figure 5.8 Convergent Patterns of Objective Function (Z) in Example (3)

Figure 5.9 Convergent Patterns of Penalty Function (g(x)) in Example (3)

Example (4):

This example illustrates the ability of the network to find the optimal decision for a network of ten bridges. Each bridge has two improvement alternatives and the budget was limited to \$3,200,000. A commercial software package for Integer Programming called DSS was used to find the optimal solution for this problem before running the network simulator. The later program found the solution in 135 seconds while the developed ANN took only 20 seconds. The network was able to converge after 6,000 iterations. The network data and the solution are available in Appendix VI. The objective function at the optima will have a value of 4,400,000. Figure 5.10 shows that the constraints were satisfied after about 500 iterations, then search was conducted for the optima until the network converged as shown in Figure 5.11.

5.3.3 Modification to the Developed Network

When the final network was fed by data about fifteen bridges, it failed to converge. A slight modification was made to the network then it was able to solve larger problems containing up to thirty bridges. This modification is to change the states of the neurons one at a time and not all of them in the same time. This would allow smaller changes to the energy function and as a result the network can easily reach a stable state. The equations governing the neuron input, the activation function and the output function remain the same without any modifications. The following example will test the network to solve a larger problem of 30 bridges. Data for a hypothetical network of bridges was used. These data are available in Appendix VI.

Example (5):

In this example, the developed neural network was able to allocate a budget of \$9.6 million to a hypothetical network of 30 bridges. Each bridge had two improvement

Figure 5.10 Convergent Patterns of Penalty Function ($g(x)$) in Example (4)

Figure 5.11 Convergent Patterns of Objective Function (Z) in Example (4)

alternatives. Figure 5.12 and 5.13 illustrate the convergent patterns of the objective function (Z) and the penalty function ($g(x)$) respectively. The network converged after 120,000 iterations which took about 3 hours of computation. It can be seen how the convergence time increases with the increase of the number of bridges. The objective function of the obtained optimal solution was \$13.2 million of benefit loss. All the available budget was allocated to the selected alternatives which are available in Appendix VII.

5.3.4 Parameters of the Final Network

The final network has four parameters that should be assigned values before running the network. These parameters are: $L(0)$, Δt , a and q . In the particular cases tested here, the determination of their suitable values required experimentations. Three constant values were established for the first three parameters and were found to be suitable for all the previous examples. The parameter values were as follows:

$$\begin{aligned} L(0) &= 0.0001; \\ \Delta t &= 0.005; \text{ and} \\ a &= 100. \end{aligned}$$

It was not possible to establish a constant value for the fourth parameter (q) which is called the "gain" of the network. This parameter appeared in eqn(5.17) which defines the activation function, and was defined as a positive scaling parameter. As implied by its definition, the function of the parameter (q) is to rescale the neuron's inputs. The maximum absolute value for the neuron inputs were recorded when the network was used to solve different sizes of bridge networks. Table 5.3 illustrates those values with the corresponding (q) values.

Regression analysis was utilized using a commercial software called "StatGraphics" in order to establish a relation between " q " and "Input _{i} ". It should be noted that the "No. of bridges" can not be used instead of "Input _{i} ". This because the values of the initial costs and

Figure 5.12 Convergent Patterns of Objective Function (Z) in Example (5)

Figure 5.13 Convergent Patterns of Penalty Function ($g(x)$) in Example (5)

Table 5.3 Values of (q) for Different Sizes of Bridge Networks

No. of Bridges	Maximum Input,	q
10	1×10^3	1000
15	1.1×10^5	2000
20	6×10^5	3500
25	5×10^7	4500
30	7×10^7	7000

benefit losses vary from one network to another. Thus the size of the network is better expressed by "Input_i", which includes both the "No. of bridges" and the initial costs and benefit losses. Using the data of Table 7.3 the following equation was obtained:

$$q = 2078 + 0.000063 \times (\text{Max. Input}_i) \quad (5.29)$$

Where: $R^2 = 0.82$, $t_1 = 3.2$, $t_2 = 3.7$ and $t_{\text{(acceptable)}}$ at 95% confidence level equal 2.13.

From this equation, the values of (q) can be estimated for different bridge networks. The (Max. Input_i) can be estimated by assuming all the (X_i)s equal to one and taking the maximum of all the (Input_i)s. This provides an approximate way to calculate the (Max. Input_i). It was also observed that reducing the gain "q" during the iteration enhanced the convergence time for some cases. It is also recommended to reduce the gain gradually in order to avoid local minima.

5.4 Comparison of D.P. and A.N.N.

In order to establish the optimal strategy for the Inner model, a comparison between the dynamic programming approach and the neural network technique was performed. A hypothetical network of 25 bridges was used for that purpose, each bridge had three improvement alternatives. The data of this network are given in Appendix VI. The comparison was performed at two different levels of budget. First, the budget was assumed to be \$8 million. The dynamic programming approach was able to find the optimal solution, which is shown in Table 5.4, in 1 minute. The neural network also found the same solution but in about 2 hours. It should be noted that the obtained solution is the only optimal solution. The associated benefit loss was \$11 million and all the available budget was used.

The same network of bridges was used again to perform the second comparison. The budget was assumed to be \$7.5 million. In this case, there are five optimal solutions. The

Table 5.4 The optimal solution for a Budget of \$8 Million

Bridge	Selected Alternative
1	3
2	2
3	2
4	3
5	3
6	3
7	2
8	2
9	3
10	3
11	3
12	2
13	2
14	3
15	3
16	3
17	2
18	2
19	3
20	3
21	3
22	2
23	2
24	3
25	3

five solutions are the same as the previous one but each solution will select alternative (1) instead of alternative (2) for one of the following bridges: 2, 7, 12, 17 or 22. Carrying out any of these solutions will exhaust all the available budget and generate a benefit loss of \$11.7 million. The dynamic programming approach found one of these solutions, which changed the selected alternative for bridge (2). The neural network was not able to find any of these optimal solutions. Instead, the neural network found what can be called "a near optimal solution". This solution is the same as the previous one when the budget was \$8 million except for bridge (12), alternative (3) was selected instead of alternative (2). This solution generated a benefit loss of \$11.4 M but the budget was exceeded by \$0.2 million.

From this comparison, one can conclude that the dynamic programming approach is superior to the neural network technique in simulating the Inner Model. The dynamic programming model can always find the optimal solution for any size of a bridge network in a very short time, when compared to the neural network approach. The neural network technique can sometimes find the optimal solution but for some kind of problems it would generate a near-optimal solution. One of the drawbacks of the developed neural network is that the convergence time increases almost exponentially with the size of the bridge network. The advantage of the neural network is that it does not require a hard disk storage space more than one Meg.Bytes, while the dynamic programming simulator requires a hard disk storage space equal to $(0.015 \times N \times B)$ Meg.Bytes; where (N) is the number of bridges and (B) is the available budget in million of dollars.

5.5 Summary

This chapter presented the findings of the research conducted to develop a single year optimization model for allocating funds to bridge projects through the neural network approach. The steps associated with the development of preliminary and final neural network model were discussed. Although neural networks have proven to be a useful tool in a variety

of problem solving areas, to the knowledge of the author, their application in bridge management has not been investigated before.

The final neural network model presented in this chapter was compared to the D.P. model presented in Chapter 4. The comparison concluded the superiority of the D.P. model. However, the neural network model has the advantage of requiring very little hard disk space compared to the D.P. model. For the present time, due to the large scale of the bridge problem, the D.P. model was selected to be used in the BMS. Although the neural network approach worked for a small number of bridges, expanding the applicability of this model to larger number of bridges needs more research and investigation.

In Chapter 4 and 5, the research performed to develop a network optimization model for bridge rehabilitation and replacement projects was presented. In the next Chapter, a maintenance optimization model will be presented. This module is developed to handle the maintenance activities and to consider the influence of the rehabilitation and replacement decisions on maintenance planning.

CHAPTER 6

DEVELOPMENT OF A MAINTENANCE OPTIMIZATION MODULE

6.1 Introduction

The definition of "maintenance" varies from one agency to another. Broadly speaking, it is any action that is performed by the agency maintenance crews and aims to avoid premature deterioration of the system. Maintenance activities can be divided into two main groups; routine maintenance and preventive maintenance (Manning and Reel, 1986). Routine maintenance activities include, but are not limited to, the following activities:

- Flushing bridge deck
- Cleaning and sealing of deck joints
- Drift removal
- Cleaning and sealing of bearing
- Cleaning of drainage system
- Maintenance of slopes and shore protection system
- Handrail painting
- Brush control at bridge site

Preventive maintenance activities include but not limited to the following:

- Deck patching
- Crack sealing
- Spot painting
- Sealing concrete surfaces
- Handrail repair
- Refastening of steel plate joints
- Repair of drainage parts
- Minor pier or abutment repair

The objective of performing these activities is to preserve bridges and to avoid premature deterioration of the network. The maintenance standards may vary from one province to another, thus the Standards Module was introduced in order to facilitate adjusting

the standards according to each province's policy. The first step in managing bridge maintenance is to determine the required activities for the whole network. This function will be performed by the Maintenance Expert Module, which was discussed together with the Standards Module in more detail in Chapter 3. The Maintenance Expert Module contains some expert systems which have to be developed according to each agency's specific standards and policies. It was assumed, as in the case in most of transportation agencies, that the required maintenance activities will be performed by the agency crews. Consequently, the output of the Maintenance Expert Module will include a list of the required activities and their associated requirements of labour and equipment expressed in terms of the required "Crew-Hours" for each activity.

The problem of managing bridge maintenance seems to be the same as the planning of rehabilitation and replacement projects. The apparent similarity exists because both problems have a list of required activities which have to be achieved with limited resources. Thus, the aim of the two models is to achieve optimal utilization of available resources. But, there is a significant difference between the two problems and this arises from the following:

- 1) The schedule of rehabilitation and replacement projects has to be taken into consideration when planning maintenance activities.
- 2) The difficulty of quantifying the benefits gained from carrying out the maintenance activities.
- 3) The resources for maintenance activities are the labour and the equipment available to the agency, and they are considered fixed for each year and can not be transferred from one year to the next.

For those reasons, the formulation of the maintenance optimization model will be different. The concept of suspension periods for maintenance activities will be introduced to consider the influence of the schedule of rehabilitation and replacement projects. Also, to overcome the difficulty of quantifying maintenance benefits, a priority factor for maintenance activities will be employed to simulate the benefits gained. Then a dynamic programming model will be formulated to allocate the available resources to maintenance activities in order to maximize the system benefits.

6.2 Influence of R&R Schedule on Maintenance Planning

Lack of coordination between maintenance activities and rehabilitation projects has been identified as a problem by researchers of pavement management systems (Fwa et al., 1990). However, none of the BMS developers or researchers, to the knowledge of the writer, considered the influence of rehabilitation and replacement schedule on bridge maintenance planning. The concept of suspension periods for maintenance activities was introduced by Fwa et al. (1990) in order to consider the effect of rehabilitation decisions on pavement maintenance planning. Fwa et al. (1990) defined the suspension period as "the length of time prior to a rehabilitation work that the maintenance activity concerned would not be carried out at all". They conducted a survey with some maintenance staff members of the six districts in the state of Indiana. The survey included the suspension periods for different maintenance activities. Performing analysis of variance (ANOVA) on the surveyed data proved the significance effects of the highway class, pavement conditions and the climatic region on suspension periods.

To implement this concept in Bridge Management Systems, a similar survey is required for bridge maintenance activities. Using the above introduced concept, the first sub-module of the Maintenance Optimization Module will be developed in the following section.

6.2.1 Suspension Sub-Module

The function of this sub-module is to decide, at the beginning of optimizing each year, which maintenance activities need to be suspended due to conflict with rehabilitation and replacement projects. Each province, using its maintenance standards and policy, has to establish suspension periods for each maintenance activity if that activity is in conflict with any rehabilitation activity. For this reason, the following term will be defined:

$I(ijkc)$ = The suspension period for maintenance activity (i) in conflict with a

rehabilitation activity (j), for a bridge on a highway of class (k) which is located in a climatic region (c).

The suspension sub-module will contain information about the values of the suspension period (I) for all possible combinations of i, j, k and c.

The input to this sub-module will include a complete schedule for R&R projects for all bridges over the whole analysis period. This input is generated by the R&R Network Optimization Module. From this schedule, the suspension sub-module, at any given year, can estimate the number of years until a bridge will receive a rehabilitation action. This would lead to the definition of a new term denoted as (Q):

$$Q_{bjt} = T_{bj} - t \quad (6.1)$$

Where:

- Q_{bjt} = the length of time, starting from year (t), until the bridge (b) will receive a rehabilitation action (j);
- T_{bj} = the year in which the bridge (b) will receive a rehabilitation action (j); and
- t = the year in which the analysis is being performed.

The input to the suspension sub-module will include also all the required maintenance activities accompanied with some data about the bridges that will receive these actions. These data include the bridge identification number, the class of the highway on which the bridge is located and the climatic region. The function of the module, is to match each maintenance activity with its suspension period and each bridge with its (Q) value. A term (K) will be introduced whose value will determine whether to suspend the maintenance activity or not.

$$K_{ibt} = Q_{bjt} - I_{ibt} \quad (6.2)$$

If $K_{ibt} \leq 0$, then the maintenance activity (i) suggested for bridge (b) will be suspended and will not be considered in the optimization of year (t).

6.3 Priority Factor for Maintenance Activities

The concept of using a priority factor for ranking rehabilitation and replacement projects was reviewed in Chapter 2. The drawbacks for its application to R&R projects was also identified. The R&R network optimization model developed in Chapter 4 was proven to be superior to all priority ranking formulas. This optimization model was based on quantifying the benefits gained from rehabilitation and replacement projects. But, as mentioned earlier in this chapter, it is very difficult to quantify the benefits gained from carrying out maintenance activities. Thus, a priority factor for maintenance activities will be employed in the Maintenance Optimization Module. It will not be used to rank the maintenance activities, instead it will be used to quantify the benefits of the maintenance activities. Hence, the model objective will be to maximize this priority factor over the whole network. The priority factor will be the second sub-module.

A deficiency-points assignment system will be borrowed from a study conducted by PennDOT (1987). The deficiency point scale ranges from 0 to 100. The higher the assignment on a maintenance activity, the higher the priority. These points assigned to each maintenance activity will be called the priority factor (PF) of this activity. The system will assign deficiency points to each activity according to four main groups. These groups are: activity ranking, activity urgency, bridge criticality and bridge adequacy. Table 6.1 summarizes these categories with their elements and weights.

Activity ranking takes into consideration the relative importance of bridge maintenance activities. It is the responsibility of each agency to establish a suitable ranking for its maintenance activities. The activity urgency factor reflects a humanized assessment of the bridge inspector, of how soon the activity should be carried out. Bridge criticality represents the importance of the bridge to the network based on three factors. These factors are: the highway classification, the department road network indicator and the impact on traffic if the bridge is closed. The fourth group of the system is the bridge adequacy which is measured

Table 6.1 Maintenance Deficiency Points Assignment

(Source: PennDOT, 1987)

Deficiency Points	Component	Element	Deficiency Points Assignment
25	Bridge maintenance activity rank	Group AF	40
		A	25
		B	20
		C	15
		D	10
		E	5
25	Activity urgency factor	Code 0	25
		1	20
		2	15
		3	10
		4	5
		5	0
25	Bridge criticality		
		Part A: Interstate	5
		US numbered highway	4
		State highway	3
		County highway	2
		City, Borough St & Twp Rd	1
		Part B: PCN	5
		PCN/coal haul	5
		Agricultural access	3
		industrial access	3
		Part C: ADT x detour length $\geq 30,000$	15
		$\geq 15,000$ but $< 30,000$	10
		$\geq 3,000$ but $< 15,000$	5
		$< 3,000$	0
25	Bridge adequacy		
		Part A: Lowest condition rating ≤ 3	15
		> 3 but ≤ 4	10
		> 4 but ≤ 5	5
		> 5	0
		Part B: Load capacity (inventory rating)	
		(H configuration) $\leq 12t$	10
		$12 < (H \text{ configuration}) \leq 20$	7
		$20 < (ML \ 80 \text{ configuration}) \leq 30$	4
		(ML 80 configuration) > 30	0

by the current load capacity and the lowest condition rating of the structure's components. The system will need some bridge data in order to estimate the priority factors. These data include the highway class, the traffic volume on the bridge, the detour length if the bridge was closed, the department road network indicator, the current load capacity of the bridge and the lowest condition rating for the bridge elements.

6.4 The Optimization Model

The optimization model will constitute the third sub-module of the Maintenance Optimization Module. The recommended maintenance activities generated by the Maintenance Expert Module will be screened by the Suspension sub-module, taking into accounts the R&R schedule generated by the R&R Network Optimization Module. The output of the Suspension sub-module will be fed to the Priority Factor sub-module to estimate the priority factor (PF) for each maintenance activity. Finally, the recommended activities will be optimized by the Optimization sub-module in order to generate the maintenance activity list. Figure 6.1 shows the different components of the Maintenance Optimization Module as well as its input and output.

The objective of the model, as stated earlier, is to maximize the total priority factor over the whole network, constrained by the labour and equipment availability. It is assumed that each agency has limited resources for each year, expressed by the available "Crew-Hours" during the whole year. The "Crew" size may vary from one agency to another and it is the responsibility of each agency to define its "Crew" in terms of labour and equipment. Due to the nature of the maintenance resources, it is not allowed to carry some resources from one year to another. This is one of the characteristics that differentiate managing maintenance activities from managing rehabilitation activities. Consequently the optimization will be carried out for each year separately, but the activities recommended for previous years will be taken into account. Therefore, there is no need for a model such as the Outer Model

Figure 6.1 Components of the Maintenance Optimization Module

described in Chapter 4 to handle the time dimension. It is assumed also that each bridge can receive more than one maintenance activity in one year. Figure 6.2 illustrates the steps of developing the recommended maintenance activity list for a network of (N) bridges, for an analysis period of (T) years. The Figure shows how the Maintenance Optimization Module interacts with other BMS modules to perform its function.

6.4.1 Mathematical Formulation

The objective function of the optimization problem for each year can be expressed by the following equation:

$$\text{Maximize } Z = \sum_{i=1}^n A_i * PF_i \quad (6.3)$$

Subject To:

$$\sum_{i=1}^n A_i * ch_i \leq CH \quad (6.4)$$

$$A_i = 1, 0 \quad (6.5)$$

Where:

- Z = total priority factor gained;
- n = total number of recommended maintenance activities for the analysis year;
- A_i = 1 if maintenance activity (i) was recommended and 0 otherwise;
- PF_i = priority factor for maintenance activity (i);
- ch_i = number of crew-hours required to carry out maintenance activity (i); and
- CH = total number of crew-hours available during the analysis year.

Figure 6.2 Steps of Preparing the Maintenance Activity List

This problem can be solved using Integer Programming if we have a small number of decision variables, or more specifically maintenance activities. Unfortunately, in most transportation agencies, the number of these activities may be up to several thousands. Thus, the Integer programming will not be able to handle such large problems. Once again, the Dynamic Programming (D.P.) will be utilized to solve this problem. As mentioned before, the Dynamic Programming is a very powerful technique for large optimization problems with few constraints.

Dynamic Programming Formulation

Stages (M): maintenance activities.

States (S): all possible levels of available crew-hours.

Decision at a stage: should this activity be carried out or not, in order to achieve the maximum total PF.

Decision update to state: what is the total (PF) if this activity was carried out, and if it was not.

Recursive value relationship:

$$f_M(S_M) = \text{Max} [U(M, S_M, A_M)] \quad \text{for } A_M = 0, 1 \quad (6.6)$$

$$U(M, S_M, A_M) = PF(A_M) + f_{M-1}(S_M - ch_M) \quad (6.7)$$

Where:

- $f_M(S_M)$ = the maximum total (PF) that can be achieved till stage (M) at state (S_M);
- A_M = 1 if alternative (M) to be carried out and 0 otherwise;
- $U(M, S_M, A_M)$ = total (PF) till stage (M) when (A_M) is chosen;
- $PF(A_M)$ = priority factor of activity (M) if $A_M = 1$, and 0 otherwise; and
- ch_M = crew-hours required to carry out activity (M).

The stages of the D.P. model are assumed to be the maintenance activities. Hence, there will be (n) stages. The states at each stage will be taken as all the possible levels of crew-hours. Thus, they begin from zero and increase in increments until the last state

becomes equal to the total available crew-hours (CH) during the whole year. At each stage (M), there will be a matrix of two columns, corresponding to the two options of carrying out the activity (M) or not carrying it out. The rows of the matrix will be the possible states. The matrix elements are the values of $U(M, S_M, A_M)$.

6.5 Application of the Optimization Model

The Dynamic Programming procedure has been demonstrated in Chapter 4. Therefore, it will not be repeated for the maintenance optimization model. But, through a numerical example, the advantage of using this model will be presented. A computer program, written in Pascal code and called "DPMaint", has been developed for this model. The user manual and Pascal code of DPMaint are available in Appendix VII.

Example (I):

Table 6.2 shows the priority factor (PF) for 25 maintenance activities for a hypothetical maintenance agency. The third column of the Table shows the required crew-hours (ch) for each activity. The activities are listed in descending order of their priority factor. The fourth and the fifth columns show the accumulated (PF) and (ch) respectively. The agency problem is to decide which activities to be carried out with its limited resources of crew-hours (CH). The problem will be solved for different amounts of (CH) using two methods; the ranking method and the developed optimization model. The ranking method, which is recommended by PennDOT (1987), is to rank the activities according to their priority factor as done in Table 6.2 then to carry out the activities at the top of the list until the resources are exhausted. Nine different levels of crew-hours (CH) were chosen to perform the comparison. Tables 6.3 and 6.4 display the results of the two methods in terms of the total (PF) achieved and the unused resources. The activities selected by the two methods are illustrated in Table 6.5. The developed model was able to allocate all the resources in seven cases of the nine, while the ranking method failed to make use of all the

Table 6.2 Data for a Hypothetical Maintenance Agency

Activity	(PF)	(ch)	Total (PF)	Total (ch)
1	97	8	97	8
2	93	3	190	11
3	91	6	281	17
4	88	5	369	22
5	84	1	453	23
6	82	4	535	27
7	79	7	614	34
8	75	3	689	37
9	73	8	762	45
10	70	2	832	47
11	66	4	898	51
12	64	5	962	56
13	61	7	1023	63
14	57	3	1080	66
15	55	2	1135	68
16	52	4	1187	72
17	48	3	1235	75
18	46	3	1281	78
19	43	8	1324	86
20	39	1	1363	87
21	37	6	1400	93
22	34	5	1434	98
23	30	7	1464	105
24	28	2	1492	107
25	20	2	1512	109

Table 6.3 Results of the Ranking Method

Resources (CH)	Total (PF) Achieved	Unused (CH)
20	281	3
40	689	3
50	832	3
55	898	4
70	1135	2
85	1281	7
90	1363	3
100	1434	2
109	1512	0

Table 6.4 Results of the Developed Model

Resources (CH)	Total (PF) Achieved	Unused (CH)
20	564	0
40	894	0
50	1019	0
55	1083	0
70	1235	0
85	1368	2
90	1405	1
100	1462	0
109	1512	0

resources available in eight cases of the nine. For large networks the effectiveness of the developed model will be highly recognized. The total (PF) achieved by the two methods were plotted, in Figure 6.3, for the nine levels of resources. The figure shows the superiority of the developed model to the ranking method. The benefits gained by using the developed model will be much higher when the available resources are less than the required, which is the case for most of the transportation agencies. The last level of resources, which is 109, represents the level that is sufficient to perform all the required activities. Only at this level, the ranking method generated the same solution as that given by the developed model. But for most transportation agencies, this is a rare case.

Table 6.5 The Activities Selected by the Two Methods

Resources (CH)	Ranking Method	DPMaint
20	1 - 3	2, 5, 6, 8, 10, 11, 15, 20
40	1 - 8	2 - 6, 8, 10, 11, 14, 15, 17, 18, 20
50	1 - 10	1 - 6, 8, 10, 11, 14, 15, 17, 18, 20, 24
55	1 - 11	1 - 6, 8, 10 - 12, 14, 15, 17, 18, 20, 24
70	1 - 15	1 - 12, 14, 15, 17, 18, 20, 24
85	1 - 18	1 - 18, 20, 24, 25
90	1 - 20	1 - 18, 20, 21, 24, 25
100	1 - 22	1 - 22, 24
109	1 - 25	1 - 25

Figure 6.3 Comparison of the Ranking Method with the Developed Model

6.6 Summary

In this chapter, a maintenance optimization module was presented. This module handles all maintenance activities performed by the maintenance crews of a transportation agency. The developed module consists of three sub-modules: the suspension sub-module, the priority factor sub-module and the optimization sub-module. The function of the first sub-module is to determine which maintenance activities need to be suspended due to conflict with rehabilitation and replacement projects. The second sub-module is responsible for estimating a priority factor for each maintenance activity. The priority factor was introduced to quantify the benefits gained from carrying out maintenance activities. The last sub-module is a dynamic programming optimization model. The objective of this optimization model is to maximize the total priority factor over the whole network, constrained by resources availability. Maintenance resources availability were represented by the available crew-hours during the whole year.

A computer program, called "DPMaint", was developed to simulate the maintenance optimization model. The application of the optimization model was demonstrated through a hypothetical example. The results of the model were compared to the Pennsylvania ranking method and the comparison showed the superiority of the developed model.

Chapter 3 presented a comprehensive framework for BMS, while Chapters 4, 5 and 6 presented network optimization models for bridge rehabilitation and replacement projects and for bridge maintenance activities. These models perform the main function of the of the BMS. The next chapter will define all data requirements and the database scheme required for the developed system will also be presented.

CHAPTER 7

THE DATABASE MODULE

7.1 Introduction

Systematic presentation of data and data structure is the function of the data models described in this chapter. The BMS modules developed in Chapters 4 to 6 required and generated a large body of data. Therefore, the data models to be presented here should be considered in the light of the BMS components and their data requirements as described earlier. Two data models are used to present the data of the system and they constitute the Database Module. These are the entity-relationship data model and the relational data model as described in the following sections.

7.2 The Entity-Relationship Model

"The entity-relationship (E-R) data model is based on a perception of a real world which consists of a set of basic objects called entities and relationships among these objects" Korth and Silbuschatz, (1991). The E-R model is a data model which displays the structure of the data at a high level of abstraction. Thus, the E-R model is different from the data flow diagrams which models the functions carried out by the system components. The main objective of the E-R model is to highlight the data structures and relationships among them, specially when presenting the modeled system to higher-level executive users in the transportation agency.

Figure 7.1 shows the E-R diagram for the BMS, developed through out this study. The rectangular boxes represent the object type, which is a set of entities whose individual

Figure 7.1 The Entity-Relationship Diagram

members can be described by one or more data element. The relationship between two or more objects is represented by a diamond. It should be noted that the special notation of "Predictor" is called an associative object, which is a relation that carries some information. It should be noted also, that the triangle labeled "ISA" is a special notation for what is called "Generalization". Generalization is "a containment relationship that exists between a higher-level entity set and one or more lower-level entity set", (Korth and Silbuschatz, 1991). In our diagram, "Repair Alternative" is the higher-level object while "Maintenance Activity" and "R&R Alternative" are lower-level objects.

7.3 The Relational Data Model

"The relational model has established itself as the primary data model for commercial data processing applications", (Korth and Silbuschatz, 1991). The relational model represents the data of a certain system by a collection of relations or tables. Each relation or table has a unique name and consists of a number of fields or columns with unique names. The design of a database scheme involves the delineation of all its relations and all their fields. Partitioning each relation to the level that prevent data redundancy is also required and it is called "Normalization". The BMS data can be grouped into four main categories:

- I) Bridge data.
- II) Data entered by the user agency.
- III) Data generated by the BMS.
- IV) Historical data.

In the remaining part of this Chapter, the relations' schemes of each group will be defined. For each relation, the primary key will be defined by underlining its attributes or fields. The primary key of a relation is "a set of one or more attributes which allows us to identify uniquely an entity in the entity set", (Korth and Silbuschatz, 1991).

I) Bridge data

This group of data includes the following relations with the identified attributes.

A) Bridge Identification:

The attributes of this relation were adopted from FWHA (1988).

- 1) **Bridge identifier** (a unique number which is assigned by the BMS)
- 2) **User-agency structure number**
- 3) **County**
- 4) **Highway district**
- 5) **Main rout mileage post**
- 6) **Secondary rout mileage post**
- 7) **Bridge name**
- 8) **Latitude**
- 9) **Longitude**
- 10) **Bridge location description**

B) Construction Inventory:

- 1) **Bridge identifier**
- 2) **Date the construction began**
- 3) **Date the construction ended**
- 4) **Construction period (without delays)**
- 5) **Contract number**
- 6) **General contractor name**
- 7) **Total cost of construction**

C) Structural Inventory:

The attributes of this relation were adopted from two sources: FWHA (1988) and Hudson et al. (1987).

- 1) **Bridge identifier**
- 2) **Structure type, Main**
- 3) **Structure type, approach spans**
- 4) **Number of spans in main unit**
- 5) **Number of approach spans**
- 6) **Length of maximum span**
- 7) **Superstructure type**
- 8) **Substructure type**
- 9) **Deck type**
- 10) **Wearing surface type**
- 11) **Year of construction**
- 12) **Structure length**
- 13) **Clear deck width**
- 14) **Right sidewalk width**
- 15) **Left sidewalk width**

- 16) Vertical clearance
- 17) Number of lanes
- 18) Design truck load
- 19) Climatic region
- 20) Type of bridge railing

D) Traffic Inventory:

- 1) Bridge identifier
- 2) ADT for right direction
- 3) ADT for left direction
- 4) Truck traffic for right direction
- 5) Truck traffic for left direction
- 6) Year of traffic count
- 7) Highway classification for main rout
- 8) Highway classification for secondary rout
- 9) Small vehicles detour length
- 10) Truck detour length
- 11) Number of accidents per 100,000 vehicles

E) Bridge conditions:

The attributes of this relation were adopted from three sources: PennDOT (1992), FWHA (1988) and Hudson et al. (1987).

- 1) Bridge identifier
- 2) Date of inspection
- 3) Structure open, posted, or closed for traffic
- 4) Approach roadway general condition rating
- 5) Embankments rating
- 6) Approach guiderail rating
- 7) Approach drainage system rating
- 8) Approach slab rating
- 9) Approach relief joints rating
- 10) Deck condition rating
- 11) Expansion joints rating
- 12) Deck drainage system rating
- 13) Deck guiderail rating
- 14) Curbs and sidewalks rating
- 15) Median barrier rating
- 16) Superstructure general condition rating
- 17) Girders rating
- 18) Stringers ratings
- 19) Floorbeams rating
- 20) Diaphragms rating
- 21) Trusses rating
- 22) Bearings rating

- 23) Drainage system (below deck) rating
- 24) Bracing rating
- 25) Steel paint condition rating
- 26) Substructure general condition rating
- 27) Abutments caps rating
- 28) Abutments above ground rating
- 29) Abutments below ground rating
- 30) Intermediate-supports caps rating
- 31) Intermediate-supports above ground rating
- 32) Intermediate-supports below ground rating
- 33) Collision protection system rating
- 34) Waterway condition rating

II) Data entered by the user agency

This group of data includes the following relations with the identified attributes.

A) Budget Distribution:

- 1) Year
- 2) Available budget

B) Available Maintenance Resources:

- 1) Year
- 2) Available crew-hours

C) Other Constraints:

- 1) Constraint number
- 2) Application year
- 3) Constraint description

D) R&R L.O.S.:

The attributes of this relation were adopted from Chen and Johnston (1987).

- 1) Highway class
- 2) ADT category
- 3) Desirable load capacity
- 4) Acceptable load capacity
- 5) Desirable lane width
- 6) Acceptable lane width
- 7) Desirable shoulder width
- 8) Acceptable shoulder width
- 9) Desirable vertical clearance
- 10) Acceptable vertical clearance

E) Routine Maintenance L.O.S.:

- 1) Routine maintenance activity code
- 2) Routine maintenance activity description
- 3) Frequency of activity

F) Preventive Maintenance L.O.S.:

- 1) Preventive maintenance activity code
- 2) Preventive maintenance activity description
- 3) Percentage of damage when exceeded, perform activity

G) Maintenance Suspension Periods:

- 1) Maintenance activity code
- 2) Rehabilitation activity code
- 3) Highway class
- 4) Climatic region
- 5) Suspension period

III) Data generated by the BMS

This group of data includes the following relations with the identified attributes.

A) Future Bridge Conditions:

- 1) Bridge identifier
- 2) Future year
- 3) Future condition rating of element (1)
- 4) Future condition rating of element (2)
-
- n+2) Future condition rating of element (n)

note: bridge elements can be obtained from the relation "Bridge Conditions"

B) R&R Activity Costs:

- 1) Rehabilitation activity cost
- 2) Activity description
- 3) Activity cost per unit

C) Future Traffic Parameters:

- 1) Bridge identifier
- 2) Future year
- 3) Future ADT
- 4) Future truck traffic
- 5) Future accidents per 100,000 vehicles

D) R&R Alternatives:

- 1) Bridge Identifier
- 2) Alternative number
- 3) Recommended year
- 4) Alternative description
- 5) benefit loss
- 6) Initial cost

E) R&R Schedule:

- 1) Year of implementation
- 2) Bridge identifier
- 3) Recommended alternative
- 4) Benefit loss
- 5) Initial cost

F) Required Maintenance Activities:

- 1) Bridge identifier
- 2) Activity code
- 3) Recommended year
- 4) Required crew-hours

G) Maintenance Schedule:

- 1) Year of implementation
- 2) Bridge identifier
- 3) Number of implemented activities
- 4) Codes of implemented activities
- 5) Required crew-hours for each activity
- 6) Total required crew-hours

H) Maintenance Priority Factor:

- 1) Bridge identifier
- 2) Maintenance activity code
- 3) Recommended year
- 4) Priority factor

I) Updated Conditions:

- 1) Bridge identifier
- 2) Inspection date
- 3) Condition rating of element (1)
- 4) Condition rating of element (2)
-
- n+2) Condition rating of element (n)

IV) Historical Data

This group of data includes the following relations with the identified attributes.

A) Conditions Over Time:

- 1) Bridge identifier
- 2) Year
- 3) Condition rating of element (1)
- 4) Condition rating of element (2)
-
- n+2) Condition rating of element (n)

B) R&R Performed Activities:

- 1) Bridge identifier
- 2) Year
- 3) Rehabilitation activity description
- 4) Activity cost
- 5) Date the construction began
- 6) Date the construction ended
- 7) Construction period (without delays)
- 8) Contract number
- 9) General contractor name
- 10) Total cost of construction

C) Maintenance Performed Activities:

- 1) Bridge identifier
- 2) Year
- 3) Performed activity codes

D) Maintenance Performance Rates

- 1) Maintenance activity code
- 2) Bridge identifier
- 3) year
- 4) Used crew-hours

CHAPTER 8

SUMMARY, CONCLUSIONS AND RECOMMENDATIONS

8.1 Introduction

This chapter summarizes the research work presented in this thesis, highlights the main conclusions and provides some recommendations for further work. A comprehensive framework for Bridge Management Systems was developed and this involved:

- 1) Development of a multi-period optimization model in order to achieve the optimum allocation of the available funds to bridge rehabilitation and replacement projects.
- 2) Development of a maintenance optimization model which provides the optimum utilization of the available resources to maintenance activities and which considers the influence of rehabilitation and replacement projects on maintenance planning.
- 3) Development of a database scheme for the proposed BMS. This database identifies all the data requirements.

8.2 Summary

The developed framework integrated existing procedures, adopted certain principles from pavement management and established new modules. The system integrates all bridge related activities in such a way that it utilizes the available resources in the most effective manner. The system incorporates nine main modules. These modules can be grouped into three groups:

A) Modules developed through out this study:

- The DataBase Module
- The Alternative Analysis Module

- The R&R Network Optimization Module
- The Maintenance Optimization Module

B) Modules newly defined, but complete development is beyond the scope of this thesis:

- The R&R Expert Module
- The Maintenance Expert Module

C) Modules adopted from previous studies:

- The Prediction Module
- The Levels of Service Module
- The Monitoring and Updating Module

Bridge activities were divided into two main groups; rehabilitation and replacement (R&R) projects and maintenance activities. Levels of service standards for the two groups were identified and the user agency was allowed to choose its own standards. The R&R Expert Module is responsible for generating all the possible R&R alternatives for all bridges. Those generated alternatives will be analyzed by the Alternative Analysis Module in order to estimate their initial costs as well as the system benefit losses associated with their implementation. In order to perform multi-period optimization, the Prediction Module predicts future bridge conditions and future traffic parameters. The R&R Expert Module and the Alternative Analysis Module perform the previous steps for each year of the analysis period using the predicted parameters. The last three modules prepare the input file to the R&R Network Optimization Module. The file contains information about all the possible R&R alternatives for each bridge if the bridge needs to be repaired at any year of the analysis period. The function of the R&R Optimization Module is to decide which bridges must be repaired each year and what are the recommended alternatives.

The next step, after preparing the schedule of the rehabilitation and replacement projects, is to prepare the maintenance activities schedule. Managing bridge maintenance begins with determining the required activities for the whole network. This is the function of the Maintenance Expert Module. This module divides maintenance activities into two groups; routine maintenance and preventive maintenance. The output of this module is a list

of all required maintenance activities associated with their requirements of labour and equipments expressed by the required "crew-hours" for each activity. The second step in managing bridge maintenance is to allocate the available maintenance resources to the required activities in order to maximize the system benefits. The output of the Maintenance Expert Module is input to the Maintenance Optimization Module, which generates a list of the recommended activities for each year of the analysis period. The influence of rehabilitation and replacement decisions on maintenance planning is considered in the optimization process.

The Monitoring and Updating Module records three groups of information and store them in appropriate files in the database. The three groups are: inspection information, the performed maintenance activities and the records of the rehabilitation and replacement projects. All bridge data and data generated by the BMs modules are stored in the database, and the database can be handled by the appropriate database management software.

8.2.1 The R&R Network Optimization Module

Despite the fact that allocating limited funds to bridge projects is a multi-period optimization problem, none of the available methods can perform such functions. The available methods can not provide optimal decisions even if they were used for a single year. A multi-period optimization model was developed in this study in order to allocate limited funds to bridge rehabilitation and replacement projects by minimizing the loss of the system benefits. The bridge problem has two dimensions; the time dimension and the network dimension. Therefore, the model consists of two combined models; the Outer model and the Inner model. The Inner model performs single year optimization, while the Outer model optimizes the system benefits over time. Both of the models were formulated using the dynamic programming approach. A computer software, called "DPBridge", was developed to simulate the developed network optimization model. DPBridge can perform single year optimization as well as multi-period optimization.

The Inner model was reformulated using the neural network approach. The objective of using the neural network was to enhance the calculation time and the hard disk storage space required by the dynamic programming approach. Several experimentations were conducted until the final neural network model was developed. The comparison between the neural network model and the dynamic programming model revealed the superiority of the dynamic programming model.

8.2.2 The Maintenance Optimization Module

The Maintenance Optimization Module was developed in order to integrate the maintenance activities in the BMS. The developed module considers the influence of the schedule of rehabilitation and replacement projects on maintenance planning and provides optimal allocation of maintenance resources to maintenance activities. The methodology developed to prepare the maintenance activity schedule consists of three steps. The first step is to determine which maintenance activities need to be suspended due to conflict with rehabilitation and replacement projects. Then, a priority factor will be estimated for each maintenance activity in order to quantify the benefits gained by its implementation. The last step is performed by a dynamic programming model in order to allocate maintenance resources to the required activities. The objective of the model is defined to be the maximization of the total priority factor over the whole network. Maintenance resources were defined to be the total available crew-hours during the whole year. A computer program, called "DPMaint", was developed to simulate the maintenance optimization model. The application of the optimization model was demonstrated through a hypothetical example.

8.2.3 Data Modelling

The stored data of the system were described at a high level of abstraction by the Entity-Relationship model. A Relational data model was developed to identify all data items.

The BMS data were grouped into four main groups: bridge data, data entered by the user agency, data generated by the BMS and historical data. The relations' schemes of each data group were defined.

8.3 Conclusions

The main conclusions based on the conception, development and implementation of the proposed Bridge Management System are as follows:

- 1) From state-of-the-art review, it was concluded that the existing BMS frameworks do not satisfy the needs of bridge networks.
- 2) A questionnaire survey, conducted by the New York DOT, indicated that most of the U.S. states and some Canadian provinces intend to adopt "Pontis", which is a BMS software developed under the sponsorship of the FHWA. Although Pontis provided the first concrete step in developing a comprehensive BMS, it has major drawbacks and they were identified.
- 3) The available priority setting schemes for bridge rehabilitation and replacement projects, which represent the core of the BMS, were reviewed. The review resulted in the conclusion that the available schemes can not perform multi-period optimization and even for a single year, the optimal decision for allocating limited funds to bridge projects can not be obtained.
- 4) For single year optimization, the D.P. Inner Model was compared to the incremental benefit/cost method, which is the most widely used method, using 25 in-service bridges in North Carolina. The comparison proved the superiority of the D.P. Inner model to the incremental benefit/cost method.
- 5) The function of the Outer Model can not be performed by any of the existing methods. The function of the Outer model was demonstrated using a hypothetical network of 50 bridges because real data were not available.
- 6) The comparison between the neural network model and the dynamic programming

model concluded the superiority of the dynamic programming model. This is because the neural network model was limited to solve problems with a maximum of 25 bridges with 3 alternatives for each bridge, while the dynamic programming model can handle any number of bridges without any limitations except for the required hard disk space. However, the neural network has the advantage of using very little of hard disk space.

- 7) The dynamic programming Inner Model is selected to be used in conjunction with the dynamic programming Outer Model. The two combined models provide a new priority setting scheme, for bridge rehabilitation and replacement projects, which can generate the optimal decisions regarding funds allocation. The developed scheme has proven to be superior to the existing schemes. Employing the developed scheme in Bridge Management Systems will result in saving a lot of the system benefit losses.
- 8) The results of the maintenance model were compared to the Pennsylvania ranking method and the comparison showed the superiority of the developed model.

8.4 Recommendations

The results of this study revealed that further research is needed to develop a fully workable and practical BMS. In particular, it is recommended that the following be further pursued:

- 1) Some of the models, developed in this study, were tested using hypothetical data for lack of actual data. The compilation of such data would enable the users of BMS to test the viability of the system in actual applications.
- 2) The R&R Expert Module and the Maintenance Expert Module need to be developed by interviewing experts in the field of bridge maintenance and rehabilitation.
- 3) Expanding the Neural Network applicability to a larger number of bridges needs further research and investigations.
- 4) Models for predicting bridge condition need further research and it is recommended

to include the effect of traffic volumes, highway classification and bridge climatic conditions on the predictive model. It is also recommended to investigate the applicability of the Backpropagation Neural Network to predicting bridge conditions. This kind of Neural Network has proven to be a powerful technique in the field of prediction and pattern recognition, especially when it is desired to include many parameters in the prediction model.

- 5) It is recommended to have a link between the BMS and other infrastructure management systems in order to coordinate the implementation of related projects.

REFERENCES

- Al-Subhi, Kamal M. Isa, Johnston, David W. and Farid, Foad (1989). *Optimizing System-Level Bridge Maintenance, Rehabilitation and Replacement Decisions*. Report FHWA/NC/89-001. FHWA, U.S. Department of Transportation.
- Al-Subhi, Kamal M., Johnston, David W. and Farid, Foad (1990). *OPBRIDGE: An Integrated Bridge Budget Forecasting and Allocation Model at the State Level*. In Transportation Research Record 1268, TRB National Research Council, Washington, D.C., pp. 95-109.
- Bakht, Baidar and Jaeger, Leslie G. (1988). *Highway Research in Canada: An Overview. Bridge Research in Progress*. In Proceedings of a Symposium funded by the National Science Foundation and sponsored by Iowa State University, Des Moines, Iowa.
- Brown, D.B. and Colson, C.W. (1975). *Cost/Benefit Optimization for the Reduction of Roadway Environment Caused Tragedies*. Montgomery, Al.
- Buckle, Ian G. (1988). *Research Needs for Short-and Medium-Span Bridges*. Bridge Research in Progress. In Proceedings of a Symposium funded by the National Science Foundation and sponsored by Iowa State University, Des Moines, Iowa.
- Burke, L.I. and Ignizio, J.P. (1992). *Neural Networks and Operation Research: an Overview*. Computers & Operation Research, Vol. 19, No. 3/4. Great Britain.
- Chen, C-J. and Johnston, D.W. (1987). *Bridge Management Under a Level of Service Concept Providing Optimum Improvement Action, Time, and Budget Prediction*. Report FHWA/NC-88-004. FHWA, U.S. Department of Transportation.
- Chinneck, J.W. (1992). *Mathematical Programming for Engineering Applications*. Course Notes, 94.504. Department of Systems and Computer Engineering, Carleton University, Ottawa, Canada.
- Conte, D., Fernando, P. and Reel, R. (1993). *Report on Pontis*. Report SO 93-02, Structural Office, Ministry of Transportation of Ontario, Toronto.
- Diaz, M.A., Carmichael III, R.F., Hudson, S.W., Moser, L.O., (1990). *A User-Friendly Data Base Module for Bridge Management Systems*. Developments in Short and Medium Span Bridges, Volume 2. In Proceedings of the Third International Conference on Short and Medium Span Bridges, Toronto.
- Farid, F., Johnston, D., Chen, C-J., Laverde, M. and Rihani, B. (1993). *Benefit-Cost Analysis for Optimal Budget Allocation to Bridges*. In Proceedings of the Fifth International Conference on Computing in Civil and Building Engineering. The American Society of

Civil Engineering. Anaheim, California.

- Farid, F., Johnston, D., Rihani, B. and Chen, C-J. (1994-a). *Feasibility of Incremental Benefit-Cost Analysis For Optimal Budget Allocation In Bridge Management Systems*. A paper presented at the Transportation Research Board annual meeting, Washington, D.C.
- Farid, F., Johnston, D., Laverde, M. and Chen, C-J. (1994-b). *Application of Incremental Benefit-Cost Analysis For Optimal Budget Allocation to Maintenance, Rehabilitation and Replacement of Bridges*. A paper presented at the Transportation Research Board annual meeting, Washington, D.C.
- Federal Highway Administration (FHWA) (1988). *Recording and Coding Guide for the Structure Inventory and Appraisal of the Nation's Bridges*. U.S. Department of Transportation, Washington, D.C.
- Federal Highway Administration (FHWA) (1989). *Bridge Management Systems*. Report FHWA-DP-71-01R, US Department of Transportation, Washington, D.C.
- Freeman, J.A. and Skapura, D.M. (1991). *Neural Networks: Algorithms, Applications, and Programming Techniques*. Addison-Wesley Publishing Company, Inc.
- Friedland, Ian M. (1988). *The National Cooperative Highway Research Program and Bridge Engineering Research*. Bridge Research in Progress. In Proceedings of a Symposium funded by the National Science Foundation and sponsored by Iowa State University, Des Moines, Iowa.
- Fwa, T.A., Sinha, K.C. and Riverson, J.D.N. (1990). Influence of Rehabilitation Decisions on Pavement-Maintenance Planning. *Journal of Transportation Engineering*, ASCE, Vol. 116, No. 2, pp. 197-212.
- Golabi, K, Thompson, P. and Hyman, W. (1992). *Pontis Technical Manual*. Pre-Released Copy prepared by Optima Inc. and Cambridge Systematic Inc. for the Federal Highway Administration.
- Haas, Hudson and Zaniewski (1994). *Modern Pavement Management*. Krieger Publishing Company.
- Hopfield, J.J. and Tank, D W. (1985). *Neural Computation of Decisions in Optimization Problems*. *Biol. Cybernet.* 52, pp. 141-152.
- Hudson, S.W., Carmichael III, R.F., Moser, L.O., Hudson, W.R. and Wilkes, W.J. (1987). *Bridge Management Systems*. National Cooperative highway Research Program Report 300. Transportation Research Board. Washington, D.C.

- Hyman, W., Hughes, D. and Dobson, T. (1983). *The Least Cost Mix of Bridge Replacement and Repair Work on Wisconsin's State Highways Over Time: A Computer Simulation*. Draft Technical Report, Wisconsin Department of Transportation, madison, WI.
- Jiang, Yi and Sinha, K.C. (1989). *The Development of Optimal Strategies for Maintenance, Rehabilitation and Replacement of Highway Bridges, Final Report Vol. 6: Bridge Performance & Optimization*. Report FHWA/IN/JHRP-89/13. Indiana Department of Transportation, Indianapolis, IN.
- Johnston, D.W. and Zia, P. (1983). *A Level-of-Service System for Bridge Evaluation*. A report prepared for the North Carolina Department of Transportation. North Carolina State University, Raleigh, North Carolina.
- Johnston, D.W. and Zia, P. (1984). *A Level-of-Service System for Bridge Evaluation*. In Transportation Research Record 962, TRB, National Research Council, Washington, D.C. pp. 1-8.
- Korth, H.F. and Silberschatz, A. (1991). *Database System Concepts*. McGraw-Hill Inc., New York, N.Y.
- Lee, H-M. and Hsu, C-C. (1990). *Neural Network Processing Through Energy Minimization With Learning Ability to the Multiconstraint Zero-One Knapsack Problem*. In Proceedings of Tools For AI Conference, Fairfax, Va, pp. 548-555.
- Lichtenstein, A.G. and Minervino, C.M. (1990). *Revision to AASHTO Manual for Maintenance Inspection of Bridges*. Developments in Short and Medium Span Bridges, Volume 2. In Proceedings of the Third International Conference on Short and Medium Span Bridges, Toronto.
- Lipkus, Stephen (1993). *NCHRP Project 12-28 (2)A Bridge Management System Software*. In Proceeding of the Fifth International Conference on Computing in Civil and Building Engineering. The American Society of Civil Engineering. Anaheim, California.
- Looi C-K. (1992). *Neural Network Methods in Combinatorial Optimization*. Computers & Operation Research, Vol. 19, No. 3/4. Great Britain.
- Manning, D.G. and Reel, R.S. (1986). *Bridge Management Practices in Ontario*. Developments in Short and Medium Span Bridges, Volume 1. Proceedings of Second International Conference on Short and Medium Span Bridges, Ottawa.
- Martin, J. (1967). *Design of Real-Time Computer Systems*. Prentic-Hall, Inc., Englewood Cliffs, New Jersey.

- McClure, R.M. Arner, R.C. Vanhorne, D.A. and Koretzky, H.P. (1986). *A Comprehensive Bridge Management System*. Developments in Short and Medium Span Bridges, Volume 1. Proceedings of second International Conference on Short and Medium Span Bridges.
- McClure, R.M. and Hoffman, G.L. (1990). *The Pennsylvania Bridge Management System*. In Proceedings of the First International Conference on Bridge Management, The University of Surrey, Guildford, UK.
- McCulloch, W.S. and Pitts, W. (1943). *A Logical Calculus of the Ideas Immanent in Nervous Activity*. Bulletin of mathematical Biophysics, 5:115-133.
- McFarland, W., Griffin, L.L, Rollins, J.B., Stockton, W.R., Phillips, D.T. and Dudek, C.L. (1979). Assessment of Techniques for Cost-Effectiveness of Highway Accident Countermeasures. Report No. FHWA-RD-79-53, prepared for the Federal Highway Administration, by Texas Transportation Institute, Texas A&M University, College Station, TX.
- McFarland, W., Rollins, J. and Dheri, R. (1983). *Documentation for Incremental Benefit-Cost Technique*. Technical Report prepared for the Federal Highway Administration, by Texas Transportation Institute, Texas A&M University, College Station, TX.
- Ministry of Transportation of Ontario (1981). *Ontario Structure Inventory System (OSIS)*. MTO, Toronto.
- Ministry of Transportation of Ontario (1991). *Ontario Structure Inspection Manual (OSIM)*. MTO, Toronto.
- National Cooperative Highway Research Program (1991). *Summary of Progress*. Transportation Research Board. Washington, D.C.
- Neter, J. Wasserman, W. and Kutner, M. (1985). *Applied Linear Statistical Models: Regression, Analysis of Variance and Experimental Designs*. Richard D. Irwing Inc., Homewood, Illinois.
- New York State Department of Transportation (1993). *Bridge Management System Survey Results*. Albany, N.Y.
- Ontario Government, Office of the Provincial Auditor (1992). *The 1992 Annual Report*. Publications Ontario, Toronto.
- Pennsylvania Department of Transportation (PennDOT) - Bridge Management Task Group (1984). *Pennsylvania Bridge Management System - Proposal Strategies to Inspect, Design, Maintain, Rehabilitate, Replace, Prioritize, and Fund Bridge Systems*. Pennsylvania, Harrisburg.

Pennsylvania Department of Transportation (PennDOT) - Bridge Management Work Group (1987). *The Pennsylvania Bridge Management System Final Report*. Report No. FHWA-PH-86-036+84-28A. Pennsylvania, Harrisburg.

Pennsylvania Department of Transportation (PennDOT) (1992). *Handout for Participants at the 6th Annual Workshop on Bridge Management Systems*. Transportation Research Board. Washington, D.C.

Pigman, J.G., et al. (1976). *Optimal Highway Safety Improvement Investments by Dynamic Programming*. Kentucky DOT.

Ramanujam, J. and Sadayappan, P. (1988). *Optimization by Neural Networks*. In Proceedings of the IEEE Second International Conference on Neural Networks, Vol. II, pp. 325-332.

Reel, R.S. and Conte, D.F. (1986). *Ontario Structure Inspection System*. Developments in Short and Medium Span Bridges, Volume 1. In Proceedings of the second International Conference on Short and Medium Span Bridges, Ottawa.

Reel, R.S. and Muruganandan, C. (1990). *Use of Financial Analysis in Bridge Rehabilitation Projects in Ontario*. Developments in Short and Medium Span Bridges, Volume 2. In Proceedings of the Third International Conference on Short and Medium Span Bridges, Toronto.

Saito, M. and Sinha, K.C. (1990). *Timing for bridge Replacement, Rehabilitation and Maintenance*. In Transportation Research Record 1268, TRB, National Research Council, Washington, D.C., pp. 75-83.

Shirol, A.M., Winkler, W.J. and Hill, J.J. (1991). *Bridge Management Systems - State of the Art*. In Transportation Research Record 1290, TRB, National Research Council, Washington, D.C., pp. 149-156.

Sobanjo, J.O. (1993). *Deterioration Models for Highway Bridges*. Proceedings of Infrastructure Planning and Management. ASCE, Denever, Colorado.

Tanimoto, Steven L. (1987). *The Elements of Artificial Intelligence: An Introduction Using Lisp*. Computer Science Press, Inc. Maryland.

Thompson, P.D., Shepard R.W. and Abd Al-Rahim, I. (1993). *Bridge Management System Implementation at CARLANDS*. In Proceedings of the Fifth International Conference on Computing in Civil and Building Engineering. The American Society of Civil Engineering. Anaheim, California.

- Wang, J. and Chankong, V. (1992). *Recurrent Neural Network for Linear Programming: Analysis and Design Principles*. Computers & Operation Research, Vol. 19, No. 3/4, Great Britain.
- Waterman, Donald A. (1986). *A Guide to Expert Systems*. Addison-Wesely Publishing Company, Inc.
- Webster's New Collegiate Dictionary (1977). Springfield, Mass., G&C Merriam Company.
- Weissmann, J., Burns, N.H. and Hudson, W.R. (1991). *Operating the Texas Eligible Bridge Selection System (TEBSS)*. Research Report conducted for the Texas Department of Transportation by the Center For Transportation Research, The University of Texas at Austin, Austin, Texas.
- Winston, W.L. (1991). *Introduction to Mathematical Programming: Applications and Algorithms*. Pws-Kent Publishing Company, Inc. Boston.
- Yourdon, E. (1989). *Modern Structured Analysis*. Prentice-Hall, Inc., Englewood Cliffs, New Jersey.

APPENDIX (I)

Data Items of the U.S.A. National Bridge Inventory

Data Items

1	State Code
2	State Highway Department District
3	County (Parish) Code
4	Place Code
5	Inventory Route
6	Features Intersected
7	Facility Carried by Structure
8	Structure Number
9	Location
10	Inventory Route, Minimum Vertical Clearance
11	Milepoint
12	Road Section Number
13	Bridge Description
14	Defense Milepoint
15	Defense Section Length
16	Latitude
17	Longitude
18	Physical Vulnerability
19	Bypass, Detour Length
20	Toll
21	Maintenance Responsibility
22	Owner
23	Federal-aid Project Number
24	Highway System
25	Administrative Jurisdiction
26	Functional Classification of Inventory Route
27	Year Built
28	Lanes On and Under the Structure
29	Average Daily Traffic
30	Year of Average Daily Traffic
31	Design Load
32	Approach Roadway Width
33	Bridge Median
34	Skew
35	Structure Flared
36	Traffic Safety Features
37	Historical Significance
38	Navigation Control
39	Navigation Vertical Clearance
40	Navigation Horizontal Clearance
41	Structure Open, Posted, or Closed to Traffic
42	Type of Service
43	Structure Type, Main
44	Structure Type, Approach Spans
45	Number of Spans in Main Unit
46	Number of Approach Spans
47	Inventory Route, Total Horizontal Clearance

48	Length of Maximum Span
49	Structure Length
50	Curb or Sidewalk Widths
51	Bridge Roadway Width, Curb-to-Curb
52	Deck Width, Out-to-Out
53	Minimum Vertical Clearance Over Bridge Roadway
54	Minimum Vertical Underclearance
55	Minimum Lateral Underclearance on Right
56	Minimum Lateral Underclearance on Left
57	Wearing Surface - Protective System
--	Condition Ratings
58	Deck
59	Superstructure
60	Substructure
61	Channel and Channel Protection
62	Culverts
63	Estimate Remaining Life
64	Operating Rating
65	Approach Roadway Alignment
66	Inventory Rating
--	Appraisal Ratings
67	Structural Evaluation
68	Deck Geometry
69	Underclearances, Vertical and Horizontal
70	Bridge Posting
71	Waterway Adequacy
72	Approach Roadway Alignment
73	Year Needed
74	Type of Service
75	Type of Work
76	Length of Structure Improvement
77	Proposed Design Loading of Improvement
78	Proposed Roadway Width
79	Proposed Number of Lanes
80	Design ADT
81	Year of Estimated ADT
82	Year of Proposed Adjacent Roadway Improvements
83	Type of Proposed Adjacent Roadway Improvements
84	Cost of Improvements
85	Preliminary Engineering
86	Demolition
87	Substructure
88	Superstructure
89	(Reserved)
90	Inspection Date
91	Designated Inspection Frequency
92	Critical Feature Inspection
93	Critical Feature Inspection Date
94	Bridge Improvement Cost
95	Roadway Improvement Cost
96	Total Project Cost

97	Year of Improvement Cost Estimate
98	Border Bridge
99	Border Bridge Structure Number
100	Defense Highway Designation
101	Parallel Structure Designation
102	Direction of Traffic
103	Temporary Structure Designation
104	Highway System of the Inventory Route
105	(Reserved)
106	Year Reconstructed
107	Deck Structure Type
108	Wearing Surface/Protective System
109	Average Daily Truck Traffic
110	Designated National Network
111	Pier or Abutment Protection (for Navigation)
112	NBIS Bridge Length
113	Scour Critical Bridges
114	Future Average Daily Traffic
115	Year of Future Average Daily Traffic
116	Minimum Navigation Vertical Clearance Vertical Lift Bridge

APPENDIX II

The "DPBridge" Computer Software: User Manual and Pascal Code

DPBridge User Manual

1.0 Introduction

The "DPBridge" is a computer software, written in Pascal code, to simulate the Dynamic Programming Model developed in Chapter 4. The main function of the DPBridge is to allocate limited funds to rehabilitation and replacement projects for a bridge network over a specified period of time. Funds allocation includes choosing the best improvement alternative for each bridge in the network with determining the optimum timing for carrying it out. Thus, DPBridge has the ability to perform multi-period optimization utilizing both of the Outer and the Inner models. It also can simulate the Inner model only to perform a single year optimization. DPBridge requires information about all the possible alternatives for all the bridges with the associated initial costs (IC) and benefit losses (BL) if the bridge to be repaired at any year of the analysis period.

2.0 Hardware Requirements

- 1) A 386 or 486 personal computer with a minimum RAM of 2 Meg. Bytes.
- 2) A hard disk space of at least $(0.015 \times N \times B)$, where (N) is the total number of bridges and (B) is the total budget for all the analysis period in million of dollars.

3.0 Program Input

The total number of bridges, length of the analysis period and the available budget for each year will be entered by the user through a user interface module. The initial costs and benefit losses of all possible alternatives for all bridges should be arranged using a specific format in ASCII files. The data of each year should be stored in a separate file. The names

of the files should be: Year1, Year2,....., YearT, where T is the length of the analysis period.

The data example listed below illustrates the input file format. Each line of the file has only two inputs. The data of all bridges will be listed in an ascending order of the bridge number, or the bridge I.D., without any space lines between bridges' data. The first line of each bridge data will contain the bridge number and the number of recommended alternatives without counting the "Do Nothing" alternative. The "Do Nothing" alternative will be always the alternative No. "0". Following this line, the initial cost and benefit loss of each alternative will be placed in a separate line.

Data Example

Required Data:

Bridge	Alternative	Initial Cost	Benefit Loss
1	0	0	300
	1	600	100
	2	1700	0
2	0	0	280
	1	100	260
	2	500	220
	3	650	0

Input File Format:

1	2
0	300
600	100
1700	0
2	3
0	280
100	260
500	220
650	0

4.0 User Interface

- 1) Type "DPBridge" on the drive that contains the "DPBridge.exe" file.
- 2) An opening screen will appear, showing the software name and its version. Press "Enter" to proceed, otherwise press [Ctrl + Break].
- 3) If you proceed, the computer will ask you to enter the following data:
 - a) The total number of bridges in your network
 - b) The length of the analysis period (in years)
 - c) The available budget for each year (in million of years)
- 4) If it is a single year optimization, the computer will ask you if you wish to see the intermediate steps or not. Answer by 1 for Yes and 2 for NO.
- 5) After entering the required data, the computer will ask you to wait.
- 6) When computations are completed, a message will appear on the screen saying: "I am done!", and the output files' names will be listed.

5.0 Program Output

- The main output file of DPBridge will include the following results:
 - 1) The recommended spending level for each year of the analysis period
 - 2) The alternative-choice decision for each year, which includes the recommended alternative for each bridge in the network. It should be noted that if for a certain year, a bridge has an alternative with the number "9", this means that this bridge received an improvement alternative in a previous year.
 - 3) The initial cost required to carry out the decision of each year
 - 4) The unused budget for each year, which is the difference between the recommended spending level and the required initial costs to carry out the recommended projects
- If the problem is a single year optimization, DPBridge can display its intermediate steps in separate files

DPBridge Pascal Code

Program DP_Bridge;

{ \$M 65520, 0, 655360 }

Uses Crt;

Const

Max_Period = 5;

MaxBudget = !5000;

MNBridge = 50;

MaxAlter = 4;

Max_State = 20;

Max_BL = 1000000;

TYPE

BridgeData = Record

 BID : ShortInt;

 NAlt : ShortInt;

 IC : Array [0..MaxAlter] of Integer;

 BL : Array [0..MaxAlter] of Integer;

End;

AllData = Array [1..MNBridge] of BridgeData;

Cell = Record

 TotalBL : LongInt;

 TotalIC : Integer;

 SpendL : Integer;

 Pre_State : Integer;

 Alter : Array [1..MNBridge] of ShortInt;

End;

Year = Array [0..Max_State] of Cell;

{ Stages }

Stage = Array [1..MaxBudget] of LongInt;

FFStage = Record

 FFS : LongInt;

 FAlt : Integer;

FPreS: Integer;
End;

VAR

IN_Steps, Pt: Integer;
ti, t, State, Spend, MaxState, MaxSpend, TBI: : Integer;
Prev_st, Counter1, Budget, stsp, NBridge : Integer;

Annual_Budget: Array [1..Max_Period] of Integer;
TNBridge, Analysis_Period : Integer;

YearData, MyData, PreYearData : AllData;
BrID : Array [1..MNBridge] of Integer;
MyCell : Cell;

MyYear : Array [1..Max_Period] of Year;

Procedure ReadData (Var A: AllData);

Var
vss, Filename : String;
DataFile : Text;
i, j, k : Integer;

Begin

Str (Pt, vss);
FileName := 'Year' + vss;
Assign (DataFile, FileName);
Reset (DataFile);
For i := 1 to TNBridge Do Begin
 ReadLn (DataFile, A [i]. BID, A [i]. NAlt);
 k := A [i]. NAlt;
 For j := 0 To k Do Begin
 ReadLn (DataFile, A [i]. IC [j], A [i]. BL [j]);
 End; {j}
End; {i}
Close (DataFile);

End; {Procedure}

OF / DE

3

Resolution test chart showing patterns of vertical and horizontal lines with numerical values: 1.0, 1.1, 1.25, 1.4, 1.6, 1.8, 2.0, 2.2, 2.5, 2.8, 3.2, 3.6, 4.0, 4.5, 5.0, 5.6, 6.3, 7.1, 8.0, 9.0, 10.

PRECISIONSM RESOLUTION TARGETS

Procedure Cell_Population;

Var

Ax, it, it1 : Integer;

Begin

Prev_St := State + Spend - Annual_Budget [t];

Counter1 := 0;

For Ax := 1 To TNBridge Do Begin

If MyYear [t - 1, Prev_St]. Alter [Ax] = 0 Then Begin

Counter1 := Counter1 + 1;

BrID [Counter1] := Ax;

End {If}

End; {Ax}

IF Counter1 > 0 Then Begin

For it := 1 To Counter1 Do Begin

MyData [it]. BID := BrID [it];

MyData [it]. NAlt := YearData [BrID [it]]. NAlt;

For it1 := 0 to MyData [it]. NAlt Do Begin

MyData [it]. IC [it1] := YearData [BrID [it]]. IC [it1];

MyData [it]. BL [it1] := YearData [BrID [it]]. BL [it1]

End {it1}

End; {it}

End; {IF}

Budget := Spend * 500; {In \$2000 increments}

NBridge := Counter1

End; {procedure}

Procedure Update_State;

Var

ii1 : Integer;

Begin

MyYear [t, State]. TotalBL := Mycell.TotalBL;

```

MyYear [t, State]. TotalIC := Mycell.TotalIC;
MyYear [t, State]. SpendL := Spend;
MyYear [t, State]. Pre_State := Prev_St;

For ii1 := 1 To TNBridge Do Begin
    MyYear [t, State]. Alter [ii1] := MyCell. Alter [ii1]
End {ii1}

End; {Procedure}

```

```

Procedure Find_Solution;

```

```

Var
OutFile : Text;
x, i, Star_State, tt, Un_Budget, tz: Integer;

```

```

Begin

```

```

Assign (OutFile, 'Output.Net');
Rewrite (OutFile);

```

```

WriteLn (OutFile, 'Total Benefit Loss = ',
        MyYear [Analysis_period, 0]. TotalBL);

```

```

Star_state := 0;
x := Analysis_period - 1;

```

```

For tt := 0 To x Do Begin
    tz := Analysis_period - tt;
    Un_Budget := (MyYear [tz, Star_State]. SpendL * 1000) -
        MyYear [tz, Star_State]. TotalIC;
    WriteLn (OutFile);
    WriteLn (OutFile);
    WriteLn (OutFile, 'Decision For Year ', tz);
    WriteLn (OutFile, '_____');
    WriteLn (OutFile);
    WriteLn (OutFile, 'Available Budget (In $Millions) = ',
        Annual_Budget [tz]);
    WriteLn (OutFile, 'Recommended Spending Level (In $Millions) = ',
        MyYear [tz, Star_State]. SpendL);
    WriteLn (OutFile, 'Required Budget (In $1000) = ',
        MyYear [tz, Star_State]. TotalIC);

```

```

WriteLn (OutFile, 'Unused Budget (In $1000) = ', Un_budget);
WriteLn (OutFile);
WriteLn (OutFile, 'Bridge  Alternative');

For i := 1 to TNBridge Do begin
    WriteLn (OutFile, i:6, ' ',
            MyYear [tz, Star_State]. Alter [i]: 6);
End; {i}

Star_state := MyYear [tz, Star_State]. Pre_State;
End; {tt}

Close (OutFile);

End; {Procedure}

```

```

Procedure DPBridge (Var AB: Cell);

```

```

VAR
Mystage : Stage;
FStage: FFStage;
m, jj, mtemp : Integer;

```

```

Procedure First_Stage (Var A: Stage);

```

```

Var
FS: LongInt;
Alt: ShortInt;
FF: Array [0..MaxAlter] of LongInt;
x: LongInt;
i, j, k, y: Integer;
F1: Text;

```

```

Begin

```

```

k := Mydata [1].NAlt;

```

```

Assign (F1, 'S1');
Rewrite (F1);
WriteLn (F1, 'STAGE (1)');
WriteLn (F1);

```



```

WriteLn (F1, 'State   f(s)   Alt');

For i := 0 to Budget Do Begin
  For j := 0 to k Do Begin
    IF Mydata [1].IC [j] <= (i * 2) Then
      FF [j] := Mydata [1].BL [j]
    Else
      FF [j] := Max_BL;
  End; {j}

  x := FF [0];
  y := 0;

  For j := 1 to k Do Begin
    IF FF [j] <= x Then Begin
      x := FF [j];
      y := j
    End {IF}
  End; {j}

  FS := x;
  Alt := y;
  A [i] := FS;

  WriteLn (F1, i:4, FS:9, Alt:6, 0:7);

End; {i}
Close (F1);

End; {Procedure}

```

```

Procedure Inter_Stages (Var A: Stage);

```

```

Var
vs, FilePath: String;
FS: LongInt;
Pres: Integer;
Alt: ShortInt;
FF: Array [0..MaxAlter] of longInt;
ss: Array [0..MaxAlter] of Integer;
i, j, z, k, y, zz, mytemp: Integer;
x: LongInt;
F2: Text;

```

Begin

k := Mydata [jj]. NAlt;

Str (jj, vs);

FilePath := 's' + vs;

Assign (F2, FilePath);

Rewrite (F2);

WriteLn (F2, 'STAGE (' , vs, ')');

WriteLn (F2);

WriteLn (F2, 'State f(s) Alt PreS');

For i := 0 To Budget Do Begin

For j := 0 To k Do Begin

IF Mydata [jj]. IC [j] <= (i * 2)

Then Begin

FF [j] := Mydata [jj]. BL [j];

mytemp := MyData [jj]. IC [j] DIV 2;

ss [j] := i - mytemp;

FF [j] := FF [j] + MyStage [ss [j]];

End

Else Begin

FF [j] := Max_BL

End {IF}

End; {For j}

x := FF [0]; {FS}

y := 0; {AL}

mytemp := MyData [jj]. IC [0] DIV 2;

z := i - mytemp; {PreS}

For j := 1 To k Do Begin

IF FF [j] <= x Then Begin

x := FF [j];

y := j;

z := ss [j]

End

End;

FS := x;

Alt := y;

PreS := z;

WriteLn (F2, i:4, FS:9, Alt:6, PreS:7);

```
End; {i}
Close (F2);
```

```
Assign (F2, FilePath);
Reset (F2);
ReadLn (F2);
ReadLn (F2);
ReadLn (F2);
For i := 0 to Budget Do begin
  ReadLn (F2, mytemp, A [i])
End;
Close (F2);
```

```
End; {Procedure}
```

```
Procedure Final_Stage (Var A: FFStage);
Var
```

```
vs, FilePath: String;
FF: Array [0..MaxAlter] of LongInt;
ss: Array [0..MaxAlter] of Integer;
i, j, k, y, z, g, mytemp: Integer;
x: LongInt;
F3: Text;
Begin
```

```
g := NBridge;
i := Budget;
k := Mydata [g]. NAlt;
```

```
For j := 0 To k Do Begin
  IF Mydata [g]. IC [j] <= (i * 2)
    Then Begin
      FF [j] := Mydata [g]. BL [j];
      mytemp := Mydata [g]. IC [j] DIV 2;
      ss [j] := i - mytemp;
      FF [j] := FF [j] + MyStage [ss [j]];
    End
    Else Begin
      FF [j] := Max_BL
    End
End; {j}
```

```

x := FF [0];    {FS}
y := 0;         {Alt}
mytemp := MyData [g]. IC [0] DIV 2;
z := i - mytemp; {PreS}

For j := 1 To k Do Begin
  IF FF [j] <= x Then Begin
    x := FF [j];
    y := j;
    z := ss [j]
  End
End;

A.FFS := x;
A.FAlt := y;
A.FPreS := z;

Str (g, vs);
FilePath := 's' + vs;
Assign (F3, FilePath);
Rewrite (F3);
WriteLn (F3, 'STAGE (', vs, ')');
WriteLn (F3);
WriteLn (F3, 'State f(s) Alt PreS');
WriteLn (F3, i:4, x:9, y:6, z:7);
Close (F3);

End;    {Procedure}

Procedure Track_Solution;

Var
  FilePath, vs: String;
  Solution: Array [1..MNBridge] of Integer;
  Total_IC, Total_BL, UN_Budget: LongInt;
  j, i, k, ps, u, v, z1, z3, z4, tx, tt: Integer;
  x, ico, z2: LongInt;
  F4, F5: Text;

Begin

  u := NBridge - 1;
  tx := FStage.FAlt;

```

```

Solution [NBridge] := tx;
ico := MyData [Nbridge].IC [tx];
Total_BL := FStage.FFS;
ps := FStage.FPreS;

For i := 1 To u Do Begin

    j := NBridge - i;

    Str (j, vs);
    FilePath := 's' + vs;
    Assign (F4, FilePath);
    Reset (F4);
    tt := ps + 3;
    For v := 1 to tt Do Begin
        ReadLn (F4)
    End;
    ReadLn (F4, z1, z2, z3, z4);
    Close (F4);

    Solution [j] := z3;
    ps := z4;
    ico := ico + MyData [j]. IC [z3]

End; {For i}

Total_IC := ico;

AB.TotalBL := Total_BL;
AB.TotalIC := Total_IC;

j := 1;
For i := 1 to TNBridge DO Begin
    If i = MyData [j]. BID Then Begin
        AB.Alter [i] := Solution [j];
        j := j + 1;
    End
    Else Begin
        AB.Alter [i] := 9
    End {If}
End {i}

End; {procedure}

```

{DPBridge Procedure}

BEGIN

IF NBridge = 2 Then Begin

First_Stage (MyStage);

Final_Stage (Fstage);

Track_Solution

End

Else If NBridge = 1 Then Begin

For jj := 0 to Budget Do Begin

MyStage [jj] := 0

End;

Final_Stage (FStage);

m := FStage. FAlt;

AB. TotalBL := FStage. FFS;

AB. TotalIC := MyData [NBridge]. IC [m];

For jj := 0 to TNBridge Do Begin

AB. Alter [jj] := 9

End;

mtemp := MyData [1]. BID;

AB. Alter [mtemp] := m

End

Else If NBridge = 0 Then Begin

For jj := 0 to TNBridge Do Begin

AB. Alter [jj] := 9

End;

AB. TotalBL := 0;

AB. TotalIC := 0

End

Else Begin

First_Stage (MyStage);

m := NBridge -1;

For jj := 2 To m Do Begin

Inter_Stages (Mystage);

End;

```

Final_Stage (Fstage);

Track_Solution;

End {Else}

END; {DPBridge Procedure}

```

```

Procedure Erase_Files;

```

```

Var
F_name, sss: String;
i: Integer;
FN : Text;

```

```

Begin

```

```

For i := 1 to TNBridge Do Begin
    Str (i, sss);
    F_Name := 's' + sss;
    Assign (FN, F_Name);
    Erase (FN);
End;

```

```

End;

```

```

Procedure Compute_BL;

```

```

Var
ix, ik: Integer;

```

```

Begin

```

```

MyCell.TotalBL := 0;

```

```

For ix := 1 to TNBridge Do Begin
    IF MyCell. Alter [ix] = 0 Then begin
        MyCell. TotalBL := MyCell. TotalBL +
            YearData [ix]. BL [0] - PreYearData [ix]. BL [0];
    End
    Else IF MyCell. Alter [ix] <> 9 Then Begin
        ik := MyCell. Alter [ix];

```

```

        MyCell. TotalBL := MyCell. TotalBL + YearData [ix]. BL [ik] +
            YearData [ix]. BL [0] -
            (2 * PreYearData [ix]. BL [0])
    End;
End; {ix}

End; {Procedure}

```

```

{Main Program}
BEGIN

```

```

    ClrScr;
    TextBackground (Blue);
    TextColor (Yellow);
    ClrScr;
    writeln;
    writeln;
    Writeln ('                DPBridge ver. 1.5 ');
    writeln;
    writeln ('                A Multi_Period Bridge Network');
    Writeln ('                Optimization Software ');
    writeln;
    writeln;
    writeln;
    writeln;
    writeln ('                By: ');
    writeln ('                Hosny A. Mohamed ');
    writeln;
    Writeln;
    writeln;
    writeln ('Press Return to continue..... ');
    Readln;
    ClrScr;
    writeln;
    writeln ('Please enter the Total Number of Bridges:');
    Readln (TNBridge);
    writeln ('Please enter the Analysis Period (in Years):');
    Readln (Analysis_Period);

```

```

For t := 1 to Analysis_Period Do Begin
    Writeln ('Please enter the Available Budget for Year ', t,
        '(in $Million):');

```



```

    ReadLn (Annual_Budget [t]);
End;

```

```

IN_Steps := 2;
IF Analysis_Period = 1 Then Begin
    WriteLn ('Do you wish to see the intermediate steps ?');
    WriteLn ('Press 1 for Yes, 2 for No: ');
    ReadLn (IN_Steps);
End;

```

```

TextBackground (Black);
ClrScr;
writeln ('Please Waite.....');

```

```

t := 1;
Pt := 1;
ReadData (MyData);

```

```

MaxState := Annual_Budget [1];
MaxSpend := Annual_Budget [1];

```

```

If Analysis_Period = 1 Then Begin
    MaxState := 0
End;

```

```

For State := 0 To MaxState DO BEGIN

```

```

    MyYear [t, State]. TotalBL := Max_BL;

```

```

If Analysis_Period = 1 Then Begin
    Spend := Annual_Budget [1];
    Budget := Annual_Budget [1] * 500;
    NBridge := TNBridge;
    DPBridge (MyCell);
    UpDate_State;
End {If Analysis_Period = 1}

```

```

Else Begin

```

```

For Spend := 0 To MaxSpend Do Begin
  stsp := State + Spend;
  IF stsp = Annual_Budget [1] Then Begin
    Budget := Spend * 500;  {in $2000 increments}
    NBridge := TNBridge;

    DPBridge (MyCell);

    If MyCell.TotalBL <= MyYear [t, State]. TotalBL
      Then Begin

        Update_State;

      End {If}
    End {IF}
  End {Spend}
End {Else}

End; {State}

IF Analysis_Period > 1 Then Begin  {Multi_Period Optimization}

For t := 2 TO Analysis_Period DO BEGIN

  Pt := t;
  ReadData (YearData);

  MaxState := 0;
  For ti := 1 to t do begin
    MaxState := MaxState + Annual_Budget [ti]
  End;
  MaxSpend := MaxState;

  IF t = Analysis_Period Then Begin
    MaxState := 0
  End;

  For State := 0 To MaxState Do Begin
    MyYear [t, State]. TotalBL := Max_BL;

    For Spend := 0 To MaxSpend Do Begin
      stsp := State + Spend;

```

```

IF stsp >= Annual_Budget [t] Then Begin

    TBD := 0;
    For ti := 1 to t do begin
        TBD := TBD + Annual_Budget [ti]
    End;

    If stsp <= TBD Then begin

        Cell_Population;

        DPBridge (MyCell);

        Pt := t - 1;
        ReadData (PreYearData);
        Compute_BL;

        MyCell.TotalBL := MyCell.TotalBL +
            MyYear [t - 1, Prev_St]. TotalBL;

        If MyCell.TotalBL <=
            MyYear [t, State]. TotalBL
        Then begin

            Update_State;
        End {If}

    End {If}
End {IF}
End {Spend}
End {State}
End; {t}

End; {Multi_Period Optimization}

Find_Solution;

If IN_Steps = 2 Then Begin
    Erase_Files
End;

ClrScr;
WriteLn ('I Am Done !');

```

```
Writeln;  
WriteLn ('Thank You For Waiting');  
Writeln;  
WriteLn ('Please Find Solution in My Output File: Output.Net');  
  
If IN_Steps = 1 Then Begin  
    Writeln;  
    WriteLn ('Intermediate solutions for each stage are available');  
    Writeln ('in files named s1, s2,..., sN');  
    Writeln ('Where N is the Total Number of Bridges');  
End;  
  
END.
```

APPENDIX III

DPBridge Output for Section 4.5.2 of Chapter 4

STAGE (1)

State	f(s)	Alt	
0	0	0	0
1	0	0	0
2	0	0	0
3	0	0	0
4	0	0	0
5	0	0	0
6	23	1	0
7	23	1	0
8	23	1	0
9	23	1	0
10	23	1	0
11	23	1	0
12	40	2	0
13	40	2	0
14	40	2	0
15	40	2	0
16	40	2	0
17	40	2	0
18	40	2	0
19	40	2	0
20	40	2	0
21	40	2	0
22	40	2	0
23	40	2	0
24	40	2	0
25	40	2	0

STAGE (2)

State	f(s)	Alt	PreS
0	0	0	0
1	0	0	1
2	0	0	2
3	3	1	0
4	3	1	1
5	3	1	2
6	23	0	6
7	23	0	7
8	23	0	8
9	26	1	6
10	26	1	7
11	26	1	8
12	40	0	12
13	40	0	13
14	40	0	14
15	43	1	12
16	43	1	13
17	43	1	14
18	43	1	15
19	43	1	16
20	43	1	17
21	43	1	18
22	43	1	19
23	43	1	20
24	43	1	21
25	43	1	22

STAGE (3)

State	f(s)	Alt	PreS
0	0	0	0
1	0	0	1
2	0	0	2
3	3	0	3
4	3	0	4
5	3	0	5
6	23	0	6
7	23	0	7
8	23	0	8
9	26	0	9
10	26	0	10
11	26	0	11
12	40	0	12
13	40	0	13
14	40	0	14
15	43	0	15
16	43	1	6
17	43	1	7
18	43	1	8
19	46	1	9
20	46	1	10
21	48	2	6
22	60	1	12
23	60	1	13
24	60	1	14
25	63	1	15

STAGE (4)

State	f(s)	Alt	PreS
25	63	0	25

Final Results:**Total Cost = 25****Net Benefit = 63****Unused Budget = 0**

Bridge	Alternative
1	2
2	1
3	1
4	0

APPENDIX IV

Input and Output of DPbridge for Application of the Outer Model

Input File for the First Year

- Initial costs and benefit losses are in \$1000

The Input File:

1	3
0	300
50	200
600	100
1700	0
2	3
0	280
100	260
500	220
650	0
3	3
0	400
70	350
750	120
1900	0
4	3
0	200
100	150
300	80
550	0
5	3
0	350
70	90
700	50
1500	0
6	3
0	400
90	80
500	20
1500	0
7	3
0	300
100	200
300	100
1200	0
8	3
0	250
50	150
300	200
700	0
9	2
0	80
30	30
200	0
10	3
0	400
150	250
650	100
1000	0

11	3
0	380
160	180
500	100
1100	0
12	3
0	250
50	190
150	70
600	0
13	2
0	70
40	20
150	0
14	3
0	200
30	150
170	50
500	0
15	3
0	300
30	200
300	50
660	0
16	3
0	400
80	360
700	130
1500	0
17	2
0	100
50	40
300	0
18	3
0	400
100	200
300	100
900	0
19	4
0	420
100	300
300	200
750	150
1400	0
20	3
0	410
120	400
800	100
1300	0
21	2
0	120
60	50
300	0
22	3
0	150
30	100

200	50
400	0
23	4
0	450
90	400
250	350
800	50
1250	0
24	3
0	350
50	300
350	200
1000	0
25	2
0	88
36	32
180	0
26	3
0	410
160	260
700	106
980	0
27	3
0	380
148	240
750	98
1020	0
28	3
0	402
150	300
720	50
1044	0
29	2
0	84
40	20
190	0
30	3
0	500
74	350
760	130
1950	0
31	3
0	300
120	250
600	50
800	0
32	3
0	160
36	110
210	58
380	0
33	2
0	78
28	20
180	0
34	3

0	410
112	198
320	130
910	0
35	3
0	420
130	390
810	98
1330	0
36	4
0	500
130	450
350	400
900	150
1500	0
37	2
0	74
42	24
160	0
38	3
0	140
34	100
210	54
380	0
39	3
0	250
54	190
310	160
700	0
40	3
0	310
38	180
250	60
650	0
41	3
0	200
100	150
300	80
550	0
42	3
0	250
50	150
300	200
700	0
43	3
0	250
50	190
150	70
600	0
44	3
0	400
80	360
700	130
1500	0
45	3
0	410

120	400
800	100
1300	0
46	3
0	350
50	300
350	200
1000	0
47	3
0	402
150	300
720	50
1044	0
48	3
0	160
36	110
210	58
380	0
49	4
0	500
130	450
350	400
900	150
1500	0
50	3
0	310
38	180
250	60
650	0

DPBridge Output for Data Set 2

- Available budget is \$2 M/year
- Analysis period is 5 years

The Output File:

Total Benefit Loss = 8453

Decision For Year 5

Available Budget (In \$Millions) = 2

Recommended Spending Level (In \$Millions) = 6

Required Budget (In \$1000) = 5980

Unused Budget (In \$1000) = 20

Bridge Alternative

1	9
2	3
3	9
4	3
5	9
6	9
7	9
8	9
9	9
10	9
11	9
12	9
13	9
14	9
15	9
16	9
17	9
18	9
19	9
20	2
21	9
22	9
23	9
24	9
25	9
26	9
27	9
28	9
29	9
30	9
31	3
32	9
33	9
34	9

35	2
36	3
37	9
38	9
39	9
40	9
41	9
42	9
43	9
44	9
45	3
46	9
47	9
48	9
49	4
50	9

Decision For Year 4

Available Budget (In \$Millions) = 2

Recommended Spending Level (In \$Millions) = 0

Required Budget (In \$1000) = 0

Unused Budget (In \$1000) = 0

Bridge	Alternative
1	9
2	0
3	9
4	0
5	9
6	9
7	9
8	9
9	9
10	9
11	9
12	9
13	9
14	9
15	9
16	9
17	9
18	9
19	9
20	0
21	9
22	9
23	9
24	9
25	9
26	9
27	9
28	9
29	9

30	9
31	0
32	9
33	9
34	9
35	0
36	0
37	9
38	9
39	9
40	9
41	9
42	9
43	9
44	9
45	0
46	9
47	9
48	9
49	0
50	9

Decision For Year 3

Available Budget (In \$Millions) = 2

Recommended Spending Level (In \$Millions) = 0

Required Budget (In \$1000) = 0

Unused Budget (In \$1000) = 0

Bridge	Alternative
1	9
2	0
3	9
4	0
5	9
6	9
7	9
8	9
9	9
10	9
11	9
12	9
13	9
14	9
15	9
16	9
17	9
18	9
19	9
20	0
21	9
22	9
23	9
24	9

25	9
26	9
27	9
28	9
29	9
30	9
31	0
32	9
33	9
34	9
35	0
36	0
37	9
38	9
39	9
40	9
41	9
42	9
43	9
44	9
45	0
46	9
47	9
48	9
49	0
50	9

Decision For Year 2

Available Budget (In \$Millions) = 2

Recommended Spending Level (In \$Millions) = 2

Required Budget (In \$1000) = 1988

Unused Budget (In \$1000) = 12

Bridge	Alternative
1	9
2	0
3	1
4	0
5	9
6	9
7	2
8	9
9	9
10	9
11	9
12	9
13	9
14	9
15	9
16	1
17	9
18	9
19	9

20	0
21	1
22	9
23	3
24	9
25	9
26	1
27	1
28	1
29	9
30	9
31	0
32	9
33	9
34	9
35	0
36	0
37	9
38	9
39	9
40	9
41	1
42	9
43	9
44	1
45	0
46	9
47	1
48	9
49	0
50	9

Decision For Year 1

Available Budget (In \$Millions) = 2

Recommended Spending Level (In \$Millions) = 2

Required Budget (In \$1000) = 1998

Unused Budget (In \$1000) = 2

Bridge	Alternative
1	1
2	0
3	0
4	0
5	1
6	1
7	0
8	1
9	1
10	1
11	1
12	2
13	1
14	1

15	1
16	0
17	1
18	1
19	1
20	0
21	0
22	1
23	0
24	1
25	1
26	0
27	0
28	0
29	1
30	1
31	0
32	1
33	1
34	1
35	0
36	0
37	1
38	1
39	1
40	1
41	0
42	1
43	2
44	0
45	0
46	1
47	0
48	1
49	0
50	1

DPBridge Output for Data Set 3

- Available budget is \$2 M/year
- Analysis period is 5 years

The Output File:

Total Benefit Loss = 9153

Decision For Year 5

Available Budget (In \$Millions) = 2

Recommended Spending Level (In \$Millions) = 6

Required Budget (In \$1000) = 5900

Unused Budget (In \$1000) = 100

Bridge Alternative

1	9
2	3
3	9
4	3
5	9
6	9
7	9
8	9
9	9
10	9
11	9
12	9
13	9
14	9
15	9
16	9
17	9
18	9
19	9
20	2
21	9
22	9
23	9
24	9
25	9
26	9
27	9
28	9
29	9
30	9
31	2

32	9
33	9
34	9
35	2
36	4
37	9
38	9
39	9
40	9
41	9
42	9
43	9
44	9
45	2
46	9
47	9
48	9
49	4
50	9

Decision For Year 4

Available Budget (In \$Millions) = 2

Recommended Spending Level (In \$Millions) = 0

Required Budget (In \$1000) = 0

Unused Budget (In \$1000) = 0

Bridge	Alternative
1	9
2	0
3	9
4	0
5	9
6	9
7	9
8	9
9	9
10	9
11	9
12	9
13	9
14	9
15	9
16	9
17	9
18	9
19	9
20	0
21	9
22	9
23	9
24	9
25	9
26	9

27	9
28	9
29	9
30	9
31	0
32	9
33	9
34	9
35	0
36	0
37	9
38	9
39	9
40	9
41	9
42	9
43	9
44	9
45	0
46	9
47	9
48	9
49	0
50	9

Decision For Year 3

Available Budget (In \$Millions) = 2

Recommended Spending Level (In \$Millions) = 0

Required Budget (In \$1000) = 0

Unused Budget (In \$1000) = 0

Bridge	Alternative
1	9
2	0
3	9
4	0
5	9
6	9
7	9
8	9
9	9
10	9
11	9
12	9
13	9
14	9
15	9
16	9
17	9
18	9
19	9
20	0
21	9

22	9
23	9
24	9
25	9
26	9
27	9
28	9
29	9
30	9
31	0
32	9
33	9
34	9
35	0
36	0
37	9
38	9
39	9
40	9
41	9
42	9
43	9
44	9
45	0
46	9
47	9
48	9
49	0
50	9

Decision For Year 2

Available Budget (In \$Millions) = 2
 Recommended Spending Level (In \$Millions) = 2
 Required Budget (In \$1000) = 1988
 Unused Budget (In \$1000) = 12

Bridge	Alternative
1	9
2	0
3	1
4	0
5	9
6	9
7	2
8	9
9	9
10	9
11	9
12	9
13	9
14	9
15	9
16	1

17	9
18	9
19	9
20	0
21	1
22	9
23	3
24	9
25	9
26	1
27	1
28	1
29	9
30	9
31	0
32	9
33	9
34	9
35	0
36	0
37	9
38	9
39	9
40	9
41	1
42	9
43	9
44	1
45	0
46	9
47	1
48	9
49	0
50	9

Decision For Year 1

Available Budget (In \$Millions) = 2

Recommended Spending Level (In \$Millions) =2

Required Budget (In \$1000) = 1998

Unused Budget (In \$1000) = 2

Bridge	Alternative
1	1
2	0
3	0
4	0
5	1
6	1
7	0
8	1
9	1
10	1
11	1

12	2
13	1
14	1
15	1
16	0
17	1
18	1
19	1
20	0
21	0
22	1
23	0
24	1
25	1
26	0
27	0
28	0
29	1
30	1
31	0
32	1
33	1
34	1
35	0
36	0
37	1
38	1
39	1
40	1
41	0
42	1
43	2
44	0
45	0
46	1
47	0
48	1
49	0
50	1

APPENDIX V

Pascal Code for the Neural Network Simulators

The Final Network Simulator

Program ANN_Bridges;

Const

epsilon1 = 0.01;

epsilon2 = 0.1;

a = 100;

W = 96;

B = 30;

m = 2;

n = 60;

n1 = 61;

Type

Neuron = Array [1..61] of Extended;

Var

BL, IC, X, U, dU, XP: Neuron;

ep, tempX, SumdLum, temp1, temp2, dt, Lum, dLum, Sum1, Sum2, Sum3, Sum4: Extended;

MaxU, MinU, Sum5, Z, g, E: Extended;

q, test2, test, counter1, counter2, i, A11, A12, j, ii: Integer;

{W, B, m, n, n1, : integer;}

F1, F2, F3: Text;

Function fun1 (z, e: extended): extended;

Begin

IF z <= e Then Begin

fun1 := 0;

End

Else IF z >= (1 - e) Then Begin

fun1 := 1;

End

Else Begin

fun1 := z

End

End;

**Function fun2 (z: extended; q: integer): extended;
Begin**

fun2 := 1 / (1 + exp (- z / q));

End;

Function fun3 (z: Integer): Extended; {dt}

Var

Y: Extended;

Begin

Y := 0.005 / z;

IF Y < 0.001 Then

fun3 := 0.001 Else

fun3 := Y

End;

Function fun4 (testq, q1: Integer): Integer; {q}

Begin

If testq > 10 then begin

If q1 > 1000 Then begin

fun4 := q1 - 500

End

Else If q1 > 100 Then begin

fun4 := q1 - 100

End

Else Begin

fun4 := q1

End

End

Else Begin

fun4 := q1

End

End;

{Main Program}

Begin

Assign (F1, 'input.ann');

Assign (F2, 'XXX.Out');

Assign (F3, 'EZg.Out');

Reset (F1);

Rewrite (F2);

Rewrite (F3);

counter1 := 1;

While Not eof(F1) Do Begin

Readln (F1, BL [counter1], IC [counter1]);

counter1 := counter1 + 1;

End;

Close (F1);

q := 7000;

Lum := 0.0001;

For i := 1 to n1 Do Begin

U [i] := 0;

X [i] := 0;

End;

For test2 := 1 to 20 do begin

dt := 0.005; { fun3 (test2); }

counter2 := 0;

For test := 1 to 5000 Do Begin

counter2 := counter2 + 1;

SumdLum := 0;

For ii := 1 to n Do Begin

{TempX := X [ii]; }

Sum4 := 0;

Sum3 := 0;

For i := 1 to n Do Begin

Sum4 := Sum4 + (IC [i] * X [i]);

Sum3 := Sum3 + X [i];

```

End;
Sum1 := Sum4 + (IC [n1] * X [n1]);

Sum2 := 0;
For j := 1 to B Do Begin
  A11 := (m * (j - 1)) + 1;
  A12 := m * j;

  temp1 := 0;
  For i := A11 to A12 Do Begin
    temp1 := temp1 + X [i];
  End;
  Sum2 := Sum2 + Sqr (temp1 - 1);
End;

dLum := 2 / (Sqr (Sum1 - W) + Sum2);

temp2 := ((IC [ii] * Sum4) + Sum3 + (IC [ii] * X [n1])
- (IC [ii] * W) - B);

dU [ii] := (a / dLum) * (BL [ii] - (Lum * temp2));

U [ii] := U [ii] - (dU [ii] * dt);

XP [ii] := fun2 ( U [ii], q);

X [ii] := fun1 (XP [ii], epsilon1);

SumdLum := SumdLum + dLum;

Sum5:= 0;
For i := 1 to n Do Begin
  Sum5 := Sum5 + BL [i] * X [i];
End;
Z := Sum5;
g := 1 / dLum;
E := Z - Lum * g;

End;    {ii}

```



```

dLum := SumdLum / n1;

dU [n1] := (-a * Lum / dLum) * (Sum1 - W);

Lum := Lum - (dLum * dt);

    IF counter2 = 1000 Then Begin
        For i := 1 to n1 Do Begin
            WriteLn (F2, X [i]: 3: 5)
        End;
        WriteLn (F2);
        WriteLn (F2);
        WriteLn (F3, E: 9: 2, Z: 9 : 2, g: 9 :2);
        counter2 := 0
    End; {IF}

End;          {test}

q := fun4 (test2, q);

End;          {test2}

For j := 1 to 4 Do Begin

    For i := 1 to n1 Do Begin
        ep := j * epsilon2;
        X [i] := fun1 (X [i], ep)
    End;

    For i := 1 to n1 Do Begin
        WriteLn (F2, X [i]: 3: 5)
    End;
    Writeln (F2);
    Writeln (F2);

End;

Close (F2);
Close (F3);
END.

```

The Preliminary Network Simulator

Program ANN;

Const

n = 2;

w = 5;

m = 2;

epsilon = 0.001;

a = 100;

b = 100;

c = 20;

d = 20;

q = 1;

Type

Neuron = Array [1..n] of Extended;

Label

One;

Var

X, BL, IC, Net, aa, XP: Neuron;

test2, test, counter1, counter2, Br, i, Al1, Al2, j, k: Integer;

Sum5, Z: Extended;

E1, Sum2, z2, E2, Sum3, z3, E3, E4: Extended;

F1, F2, F3: Text;

Function fun1 (z: extended): extended;

Begin

IF z <= 0 Then

fun1 := 0 Else

fun1 := (z)

End;

Function fun2 (z: extended): extended;

Begin

IF z = 0 Then

fun2 := 0 Else

fun2 := sqr (z);

End;

```

Function fun3 (z: extended): extended;
Begin
    fun3 := 4 * z * sqr (z) - 6 * sqr (z) + 2 * z
End;

```

```

Function fun4 (z: extended): extended;
Begin
    IF z <= epsilon    Then Begin
        fun4 := 0;
    End

    Else IF z >= (1 - epsilon)    Then Begin
        fun4 := 1;
    End

    Else Begin
        fun4 := z
    End
End;

```

```

Function fun7 (x, y: Integer): Integer;
Begin
    If x <= y then begin
        fun7 := 1;
    End

    Else If (x Mod y) <> 0 then begin
        fun7 := (x Div y) + 1;
    End

    Else Begin
        fun7 := x Div y;
    End
End;

```

```

Function fun5 (z: extended): extended;
Begin

    fun5 := 1 / (1 + exp (- z / q));

End;

```

Function fun6 (z: extended): extended;

Begin

IF z < 0 Then Begin

fun6 := 0;

End

Else Begin

fun6 := 1;

End

End;

{Main Program}

Begin

Assign (F1, 'c:\hosny\ann-prop\temp\input.ann');

Assign (F2, 'c:\hosny\ann-prop\temp\XXX.Out');

Assign (F3, 'c:\hosny\ann-prop\temp\ezg.out');

Reset (F1);

Rewrite (F2);

Rewrite (F3);

counter1 := 1;

While Not eof(F1) Do Begin

X [counter1] := 0;

ReadLn (F1, BL [counter1], IC [counter1]);

counter1 := counter1 + 1;

End;

Close (F1);

for test2 := 1 to 10 Do Begin

counter2 := 0;

For test := 1 to 10000 Do Begin

counter2 := counter2 + 1;

One: For i := 1 to n Do

Begin

Br := fun7 (i, m);

```

E1 := a / BL [i];

  Sum2 := 0;
  For j := 1 to n Do Begin
    Sum2 := Sum2 + IC [j] * X [j];
  End;
  z2 := Sum2 - w;
E2 := - b * IC [i] * fun1 (z2);

  Sum3 := 0;
  Al1 := (m * (Br - 1)) + 1;
  Al2 := m * Br;
  For k := 1 to m Do Begin
    Sum3 := Sum3 + X [k]
  End;
  z3 := Sum3 - 1;
E3 := - c * fun2 (z3);

E4 := - d * fun3 (X [i]);

Net [i] := E1 + E2 + E3 + E4;

aa [i] := fun5 (Net [i]);

XP [i] := fun4 (aa [i]);

End; {i to n Loop}

For i := 1 to n Do Begin
  X [i] := XP [i];
End;

Sum5 := 0;
For i := 1 to n Do Begin
  Sum5 := Sum5 + BL [i] * X [i];
End;
Z := Sum5;

```

IF counter2 = 1000 Then Begin

For i := 1 to n Do Begin

WriteLn (F2, X [i]: 3: 5)

End;

WriteLn (F2);

WriteLn (F2);

Writeln (F3, Z: 9: 2);

counter2 := 0

End;

{

For i := 1 to n Do Begin

IF (X [i] < 1) and (X [i] < 0) Then

GoTo One;

End;

}

End; {test}

End; {test2}

For i := 1 to n Do Begin

WriteLn (F2, X [i]: 3: 5, BL [i]: 9: 2, IC [i]: 9)

End;

Close (F2);

Close (F3);

END.

APPENDIX VI

Data for the Examples of Chapter 5

Table VI.1 Data for Example (4)

Bridge	Alternative	Benefit Loss	Initial Costs	Solution
1	1	200,000	600,000	0
	2	500,000	300,000	1
2	1	300,000	500,000	1
	2	700,000	200,000	0
3	1	400,000	200,000	1
	2	700,000	200,000	0
4	1	200,000	600,000	0
	2	500,000	300,000	1
5	1	200,000	600,000	0
	2	500,000	300,000	1
6	1	200,000	600,000	0
	2	500,000	300,000	1
7	1	300,000	500,000	1
	2	700,000	200,000	0
8	1	400,000	200,000	1
	2	700,000	200,000	0
9	1	200,000	600,000	0
	2	500,000	300,000	1
10	1	200,000	600,000	0
	2	500,000	300,000	1

Table VI.2 Data for Example (5)

Bridge	Alternative	Benefit Loss	Initial Costs	Solution
1	1	200,000	600,000	0
	2	500,000	300,000	1
2	1	300,000	500,000	1
	2	700,000	200,000	0
3	1	400,000	200,000	1
	2	700,000	200,000	0
4	1	200,000	600,000	0
	2	500,000	300,000	1
5	1	200,000	600,000	0
	2	500,000	300,000	1
6	1	200,000	600,000	0
	2	500,000	300,000	1
7	1	300,000	500,000	1
	2	700,000	200,000	0
8	1	400,000	200,000	1
	2	700,000	200,000	0
9	1	200,000	600,000	0
	2	500,000	300,000	1
10	1	200,000	600,000	0
	2	500,000	300,000	1
11	1	200,000	600,000	0
	2	500,000	300,000	1
12	1	300,000	500,000	1
	2	700,000	200,000	0

Table VI.2 Data for Example (5) (Continued)

Bridge	Alternative	Benefit Loss	Initial Costs	Solution
13	1	400,000	200,000	1
	2	700,000	200,000	0
14	1	200,000	600,000	0
	2	500,000	300,000	1
15	1	200,000	600,000	0
	2	500,000	300,000	1
16	1	200,000	600,000	0
	2	500,000	300,000	1
17	1	300,000	500,000	1
	2	700,000	200,000	0
18	1	400,000	200,000	1
	2	700,000	200,000	0
19	1	200,000	600,000	0
	2	500,000	300,000	1
20	1	200,000	600,000	0
	2	500,000	300,000	1
21	1	200,000	600,000	0
	2	500,000	300,000	1
22	1	300,000	500,000	1
	2	700,000	200,000	0
23	1	400,000	200,000	1
	2	700,000	200,000	0
24	1	200,000	600,000	0
	2	500,000	300,000	1

Table VI.2 Data for Example (5) (Continued)

Bridge	Alternative	Benefit Loss	Initial Costs	Solution
25	1	200,000	600,000	0
	2	500,000	300,000	1
26	1	200,000	600,000	0
	2	500,000	300,000	1
27	1	300,000	500,000	1
	2	700,000	200,000	0
28	1	400,000	200,000	1
	2	700,000	200,000	0
29	1	200,000	600,000	0
	2	500,000	300,000	1
30	1	200,000	600,000	0
	2	500,000	300,000	1

Table VI.3 Data for The D.P. & A.N.N. Comparison

Bridge	Alternative	Benefit Loss	Initial Costs	Solution
1	1	1000,000	0	0
	2	200,000	600,000	0
	3	500,000	300,000	1
2	1	1000,000	0	0
	2	300,000	500,000	1
	3	700,000	200,000	0
3	1	1000,000	0	0
	2	400,000	200,000	1
	3	700,000	200,000	0
4	1	1000,000	0	0
	2	200,000	600,000	0
	3	500,000	300,000	1
5	1	1000,000	0	0
	2	200,000	600,000	0
	3	500,000	300,000	1
6	1	1000,000	0	0
	2	200,000	600,000	0
	3	500,000	300,000	1
7	1	1000,000	0	0
	2	300,000	500,000	1
	3	700,000	200,000	0
8	1	1000,000	0	0
	2	400,000	200,000	1
	3	700,000	200,000	0
9	1	1000,000	0	0
	2	200,000	600,000	0
	3	500,000	300,000	1

Table VI.3 Data for The D.P. & A.N.N. Comparison (Continued)

Bridge	Alternative	Benefit Loss	Initial Costs	Solution
10	1	1000,000	0	0
	2	200,000	600,000	0
	3	500,000	300,000	1
11	1	1000,000	0	0
	2	200,000	600,000	0
	3	500,000	300,000	1
12	1	1000,000	0	0
	2	300,000	500,000	1
	3	700,000	200,000	0
13	1	1000,000	0	0
	2	400,000	200,000	1
	3	700,000	200,000	0
14	1	1000,000	0	0
	2	200,000	600,000	0
	3	500,000	300,000	1
15	1	1000,000	0	0
	2	200,000	600,000	0
	3	500,000	300,000	1
16	1	1000,000	0	0
	2	200,000	600,000	0
	3	500,000	300,000	1
17	1	1000,000	0	0
	2	300,000	500,000	1
	3	700,000	200,000	0
18	1	1000,000	0	0
	2	400,000	200,000	1
	3	700,000	200,000	0

Table VI.3 Data for The D.P. & A.N.N. Comparison (Continued)

Bridge	Alternative	Benefit Loss	Initial Costs	Solution
19	1	1000,000	0	0
	2	200,000	600,000	0
	3	500,000	300,000	1
20	1	1000,000	0	0
	2	200,000	600,000	0
	3	500,000	300,000	1
21	1	1000,000	0	0
	2	200,000	600,000	0
	3	500,000	300,000	1
22	1	1000,000	0	0
	2	300,000	500,000	1
	3	700,000	200,000	0
23	1	1000,000	0	0
	2	400,00	200,000	1
	3	700,000	200,000	0
24	1	1000,000	0	0
	2	200,000	600,000	0
	3	500,000	300,000	1
25	1	1000,000	0	0
	2	200,000	600,000	0
	3	500,000	300,000	1

APPENDIX VII

The "DPMaint" Computer Program User Manual and Pascal Code

DPMaint User Manual

1.0 Introduction

The "DPMaint" is a computer program, written in Pascal code, to simulate the Maintenance Optimization Model developed in Chapter 6. The main function of DPMaint is to allocate limited maintenance resources to maintenance activities required by a bridge network. DPMaint performs only a single year optimization. It requires information about all the required maintenance activities. These information will include the required resources to perform each activity expressed in crew-hours, and the priority factor (PF) for each activity. (PF) has been defined in Chapter 6. The total crew-hours available during the year will be supplied by the user agency also.

2.0 Hardware Requirements

- 1) A 386 or 486 personal computer with a minimum RAM of 2 Meg. Bytes.
- 2) A hard disk space of at least $(3 \times M \times CH \times 10^{-5})$, where (M) is the total number of maintenance activities and (CH) is the total crew-hours available during the year.

3.0 Program Input

The total number of maintenance activities and the available resources, expressed in crew-hours, will be entered by the user through a user interface module. The required resources and the priority factor (PF) for each maintenance activity should be arranged using a specific format in an ASCII file. The file should be named "Input.MN". Each line of the file will contain the information of only one activity. These information are three inputs and they are: the activity number, the activity (PF), and the required resources for this activity.

4.0 User Interface

- 1) Type "DPMaint" on the drive that contains the "DPMaint.exe" file.
- 2) An opening screen will appear, showing the software name and its version. Press "Enter" to proceed, otherwise press [Ctrl + Break].
- 3) If you proceed, the computer will ask you to enter the following data:
 - a) The total number of required maintenance activities
 - b) The available resources (in crew-hours)
- 4) The computer will ask you if you wish to see the intermediate steps or not. Answer by 1 for Yes and 2 for NO.
- 5) After entering the required data, the computer will ask you to wait.
- 6) When computations are completed, a message will appear on the screen saying: "I am done!", and the output files' names will be listed.

5.0 Program Output

- The main output file of DPMaint will include the following results:
 - 1) The recommended maintenance activities to be carried out this year. All the activities will be listed in the output file associated with its decision, "1" means to carry out this activity and "0" means not to do it.
 - 2) The total priority factor (PF) achieved by carrying out the DPMaint decision
 - 3) The unused resources.
- DPMaint can display its intermediate steps in separate files if the user asked for it.

DPMaint Pascal Code

Program DPMaintenance;

{ \$M 65520, 0, 655360 }

Uses Crt;

Const

M_CHS = 1000;

M_NActivity = 50;

TYPE

{Data}

Activitydata = Record

ch : Array [0..1] of Integer;

PF : Array [0..1] of Integer;

End;

Alldata = Array [1..(M_NActivity + 1)] of Activitydata;

{Stages}

Stage = Array [1..M_CHS] of LongInt;

FFStage = Record

FFS : LongInt;

FAlt : Integer;

FPreS: Integer;

End;

VAR

IN_Steps, Mytemp : Integer;

Mydata : Alldata;

Mystage : Stage;

FStage: FFStage;

counter, ii, jj, n, m : Integer;

DataFile: Text;

CHS, NActivity: Integer;

Procedure First_Stage (Var A: Stage);

Var

FS: Array [0..M_CHS] of LongInt;

Alt: Array [0..M_CHS] of ShortInt;

FF: Array [0..1] of LongInt;

i, j: Integer;

F1: Text;

Begin

For i := 0 to CHS Do Begin

For j := 0 to 1 Do Begin

IF Mydata [1].ch [j] <= i Then

FF [j] := Mydata [1].PF [j]

Else

FF [j] := 0;

End; {j}

IF FF [1] > FF [0] Then Begin

FS [i] := FF [1];

Alt [i] := 1

End

Else Begin

FS [i] := FF [0];

Alt [i] := 0

End

End; {i}

Assign (F1, 'S1');

Rewrite (F1);

WriteLn (F1, 'STAGE (1)');

WriteLn (F1);

WriteLn (F1, 'State f(s) Alt');

For i := 0 to CHS Do Begin

WriteLn (F1, i:4, FS [i]:9, Alt [i]:6);

End; {i}

Close (F1);

For i := 0 to CHS Do Begin

A [i] := FS [i]

End {i}

End; {Procedure}

Procedure Inter_Stages (Var A: Stage);

Var

vs, FilePath: String;

FS: Array [0..M_CHS] of LongInt;

Pres: Array [0..M_CHS] of Integer;

Alt: Array [0..M_CHS] of ShortInt;

FF: Array [0..1] of longInt;

ss: Array [0..1] of Integer;

i, j, zz: Integer;

F2: Text;

Begin

For i := 0 To CHS Do Begin

For j := 0 To 1 Do Begin

IF Mydata [jj]. ch [j] <= i

Then Begin

FF [j] := Mydata [jj]. PF [j];

ss [j] := i - Mydata [jj]. ch [j];

FF [j] := FF [j] + MyStage [ss [j]];

End

Else Begin

FF [j] := 0

End {IF}

End; {For j}

If FF [1] > FF [0] Then Begin

FS [i] := FF [1];

Alt [i] := 1;

PreS [i] := ss [1]

End

Else Begin

FS [i] := FF [0];

Alt [i] := 0;

PreS [i] := ss [0]

End

End; {For i}

```

For i := 0 to CHS Do Begin
  A [i] := FS [i]
End;

Str (jj, vs);
FilePath := 's' + vs;
Assign (F2, FilePath);
Rewrite (F2);
WriteLn (F2, 'STAGE (', vs, ')');
WriteLn (F2);
WriteLn (F2, 'Stat   f(s)   Alt   PreS');
For i := 0 to CHS Do Begin
  WriteLn (F2, i:4, FS [i]:9, Alt [i]:6, PreS [i]:7);
End;
Close (F2)

End;   {Procedure}

```

Procedure Final_Stage (Var A: FFStage);

```

Var
vs, FilePath: String;
FF: Array [0..1] of LongInt;
ss: Array [0..1] of Integer;
j, g: Integer;
F3: Text;

Begin

g := NActivity;

  For j := 0 To 1 Do Begin
    IF Mydata [g]. ch [j] <= CHS
      Then Begin
        FF [j] := Mydata [g]. PF [j];
        ss [j] := CHS - Mydata [g]. ch [j];
        FF [j] := FF [j] + MyStage [ss [j]];
      End
      Else Begin
        FF [j] := 0
      End
  End;
  {j}

```

If FF [1] > FF [0] Then Begin

 A.FFS := FF [1];

 A.FAlt := 1;

 A.FPreS := ss [1]

End

Else Begin

 A.FFS := FF [0];

 A.FAlt := 0;

 A.FPreS := ss [0]

End;

Str (g, vs);

FilePath := 's' + vs;

Assign (F3, FilePath);

Rewrite (F3);

WriteLn (F3, 'STAGE (' , vs, ')');

WriteLn (F3);

WriteLn (F3, 'State f(s) Alt PreS');

WriteLn (F3, CHS:4, A.FFS:9, A.FAlt:6, A.FpreS:7);

Close (F3);

End; {Procedure}

Procedure Track_Solution;

Var

FilePath, vs: String;

Solution: Array [1..M_NActivity] of Integer;

Total_ch, Total_PF, UN_CH: LongInt;

j, i, k, ps, u, v, z1, z3, z4, t, tt: Integer;

x, ico, z2: LongInt;

F4, F5: Text;

Begin

u := NActivity - 1;

t := FStage.FAlt;

Solution [NActivity] := t;

ico := MyData [NActivity].ch [t];

Total_PF := FStage.FFS;

ps := FStage.FPreS;

```

For i := 1 To u Do Begin
  j := NActivity - i;

  Str (j, vs);
  FilePath := 's' + vs;
  Assign (F4, FilePath);
  Reset (F4);
  tt := ps + 3;
  For v := 1 to tt Do Begin
    ReadLn (F4)
  End;
  ReadLn (F4, z1, z2, z3, z4);
  Close (F4);

  Solution [j] := z3;
  ps := z4;
  ico := ico + MyData [j]. ch [z3]

End; {For i}

Total_ch := ico;
UN_CH := CHS - ico;

Assign (F5, 'output.mn');
Rewrite (F5);
WriteLn (F5, 'Total (ch) = ', Total_ch);
WriteLn (F5, 'Total (PF) = ', Total_PF);
WriteLn (F5, 'Unused Resources = ', UN_CH);
WriteLn (F5, 'Activity Decision');
For i := 1 to NActivity Do Begin
  WriteLn (F5, i:6, ' ', Solution [i]:6);
End;
Close (F5)

End; {procedure}

Procedure Erase_Files;

Var
F_name, sss: String;
i: Integer;
FN : Text;

```

Begin

For i := 1 to NActivity Do Begin

Str (i, sss);

F_Name := 's' + sss;

Assign (FN, F_Name);

Erase (FN);

End;

End;

{Main Program}

BEGIN

ClrScr;

TextBackground (Blue);

TextColor (Yellow);

ClrScr;

writeln;

writeln;

Writeln (' DPMaint ver. 1.4 ');

writeln;

writeln (' A Bridge Maintenance');

WriteLn (' Optimization Software ');

writeln;

writeln;

writeln;

writeln;

writeln (' By: ');

writeln (' Hosny A. Mohamed ');

writeln;

Writeln;

writeln;

writeln ('Press Return to continue..... ');

Readln;

ClrScr;

writeln;

writeln ('Please enter the Number of Maintenance Activities:');

Readln (NActivity);

WriteLn ('Please enter the Available Resources (in Crew-Hour:');

ReadLn (CHS);

IN_Steps := 2;


```

WriteLn ('Do you wish to see intermediate steps ?');
WriteLn ('Press 1 for Yes, 2 for No: ');
ReadLn (IN_Steps);

```

```

TextBackGround (Black);
ClrScr;
writeln ('Please Waite.....');

```

```

For counter := 1 to (NActivity + 1) Do Begin
    Mydata [counter]. PF [0] := 0;
    Mydata [counter]. ch [0] := 0
End;

```

```

Assign (DataFile, 'input.mn');
Reset (DataFile);

```

```

For counter := 1 to (NActivity + 1) Do Begin
    ReadLn (DataFile, mytemp, Mydata [counter]. PF [1], Mydata
[counter]. ch [1]);
End; {For counter}

```

```

Close (DataFile);

```

```

First_Stage (Mystage);

```

```

m := NActivity -1;

```

```

For jj := 2 To m Do Begin

```

```

    Inter_Stages (Mystage);

```

```

End;

```

```

Final_Stage (Fstage);

```

```

Track_Solution;

```

```

If IN_Steps = 2 Then Begin
    Erase_Files
End;

```

```

ClrScr;

```

```
WriteLn ('I Am Done !');  
Writeln;  
WriteLn ('Thank You For Waiting');  
Writeln;  
WriteLn ('Please Find Solution in My Output File: Output.MN');  
  
If IN_Steps = 1 Then Begin  
    Writeln;  
    WriteLn ('Intermediate solutions for each stage are available');  
    WriteLn ('in files named s1, s2,...., sM');  
    WriteLn ('Where M is Number of Maintenance Activities');  
End;  
  
END.
```

END

| 0 6 | 0 6 - 9 | 6

FIN