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A Decision Support System for the Design of Cost-Effective Metropolitan Area Networks

Thesis Report
Systems Science Programme
University of Ottawa

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Abstract

The objective of this thesis was to develop the required tools to solve a relatively comprehensive telecommunications network design optimisation problem. It can be summarised as a Minimum Cost-Flow Capacitated Network Design Problem with multiple facilities, multiple commodities and constrained by performance and survivability requirements. The resulting optimisation model is supported by one mixed-integer/linear mathematical programming formulation and implemented in a 32-bit GUI-based network design tool for automation purposes.

Throughout its development, the model was tested and validated with randomly generated design problems. The base case application, from which the design requirements were derived, is the National Defence Headquarters (NDHQ) Metropolitan Area Network (MAN). The area of interest on the NDHQ MAN is the inter-building router backbone, where expensive leased facilities are installed to inter-connect buildings routers. As a result of this thesis, an interactive tool was developed, which provides network design and analysis capabilities. Its impact on the NDHQ MAN was lowered because of the limitations in the data available and significant changes to the network environment, but the results obtained proved very insightful in validating the performance and accuracy of the model.

Acknowledgements

Two important contributors to the thesis are Sophie Martel from the Network Planning Section of the NDHQ MAN, who provided significant insights into the target application, and Dr. Alain Martel, from Université Laval, for his valuable modelling advises and support with the Cplex solver.

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Acronyms

ADSL	Asymmetrical Digital Subscriber Line
ATM	Asynchronous Transfer Mode
bps	Bits per second
CF	Canadian Forces
CNDP	Capacitated Network Design Problem
csv	Comma Separated Values
DLL	Dynamic Link Library
DND	Department of National Defence
DS1	Digital Signal level 1
DSA	Digital Signal level A
DWAN	Defence Wide Area Network
ETEDR	End-to-end Delay Requirement
IEEE	Institute of Electrical and Electronic Engineers
IP	Internet Protocol
ISDN	Integrated Services Digital Network
Kbps	Kilobits per seconds
LAN	Local Area Network
LP	Linear Program
MAN	Metropolitan Area Network
Mbps	Megabits per seconds
MCSN	Minimum Cost Survivable Network
MCST	Minimum Cost Survivable Topology
MIP	Mixed Integer Program
MRC	Monthly Recurring Charges
MST	Minimum Spanning Tree
NDHQ	National Defence Headquarters
NDOT	Network Design Optimisation Tool
NPV	Net Present Value
OD	Origin-Destination
OSPF	Open Shortest Path First
pps	Packets per second
PVC	Private Virtual Circuit
RFC	Request For Comments
RNG	Random Network Generator
SC	Service Charges
SLC	Service Level Commitment
SP	Shortest Path
TDM	Time Division Multiplexing
TFLP	Two-Facility Loading Problem
TOS	Type Of Service
TSP	Telecommunications Service Provider

Introduction

In today's Information Age, users at all levels are increasingly dependent on network-based information technology services. From a network engineering perspective, survivability and performance considerations are therefore vital to any design recommendation. In addition to these technical requirements, in the current economical climate, the design of telecommunication networks entails not only the provision of viable technical solutions, but also the choice of an economical alternative. Therefore the challenge is to design modern telecommunication networks that will satisfy all the essential technical requirements at minimum possible cost. This is also true of the National Defence Headquarters (NDHQ) Metropolitan Area Network (MAN) which served as the base-case application for the purpose of this thesis. More specifically, the area of interest is the inter-building backbone[1], where expensive facilities are leased from Telecommunication Service Providers (TSPs).

Summary of contributions

As a result of this thesis, a Decision Support System to solve a comprehensive communication network design problem was developed and validated. The large amount of design requirements considered by the model called for some modelling elements not found in the literature. More specifically, from a mathematical programming perspective, the modification of the classical link capacity constraint and development of a node capacity constraint based on the M/M/1 queuing model were required to incorporate performance requirements into the model. Also, the adjunction of an ancillary objective function helps the model to represent the behaviour of the OSPF routing protocol allocating the traffic flows within the obtained minimum cost design solution. Finally, this thesis provides extensive results derived from random networks and a base-case application used to validate the performance and accuracy of the model.

Thesis report overview

To model this complex system, a step-wise problem solving approach was adopted. Specifically, Chapter 1 combines the "Problem Definition" and "Value System Design" steps

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[1] To lighten the document, the NDHQ MAN inter-building backbone will be referred to as the NDHQ MAN from this point on.

from Hill [1972], in the context of the NDHQ MAN. Chapter 2 contains a literature review and the development of the mathematical programming formulation of the model. Chapter 3 describes the implementation of the model in the Network Design Optimisation Tool (NDOT) and the derivation of the parameters of the model. The results obtained through NDOT are summarised in Chapter 4. Finally, an assessment of the success of this thesis and recommendations for future work are presented in the conclusion.

Chapter 1

Problem definition

The intent of this chapter is to identify all the key elements required to effectively model the problem under study in this thesis. This approach yields valuable insight into the problem and ensures that all the important problem elements are considered. Specifically, Section 1.1. provides background information on the NDHQ MAN, while the remaining sections provide a detailed description of the key elements of the NDHQ MAN system which need to be considered to efficiently solve this problem. These elements correspond to the system components, needs, inputs, constraints, alterables and outputs. Figure 1-1 provides a graphical overview of the system.

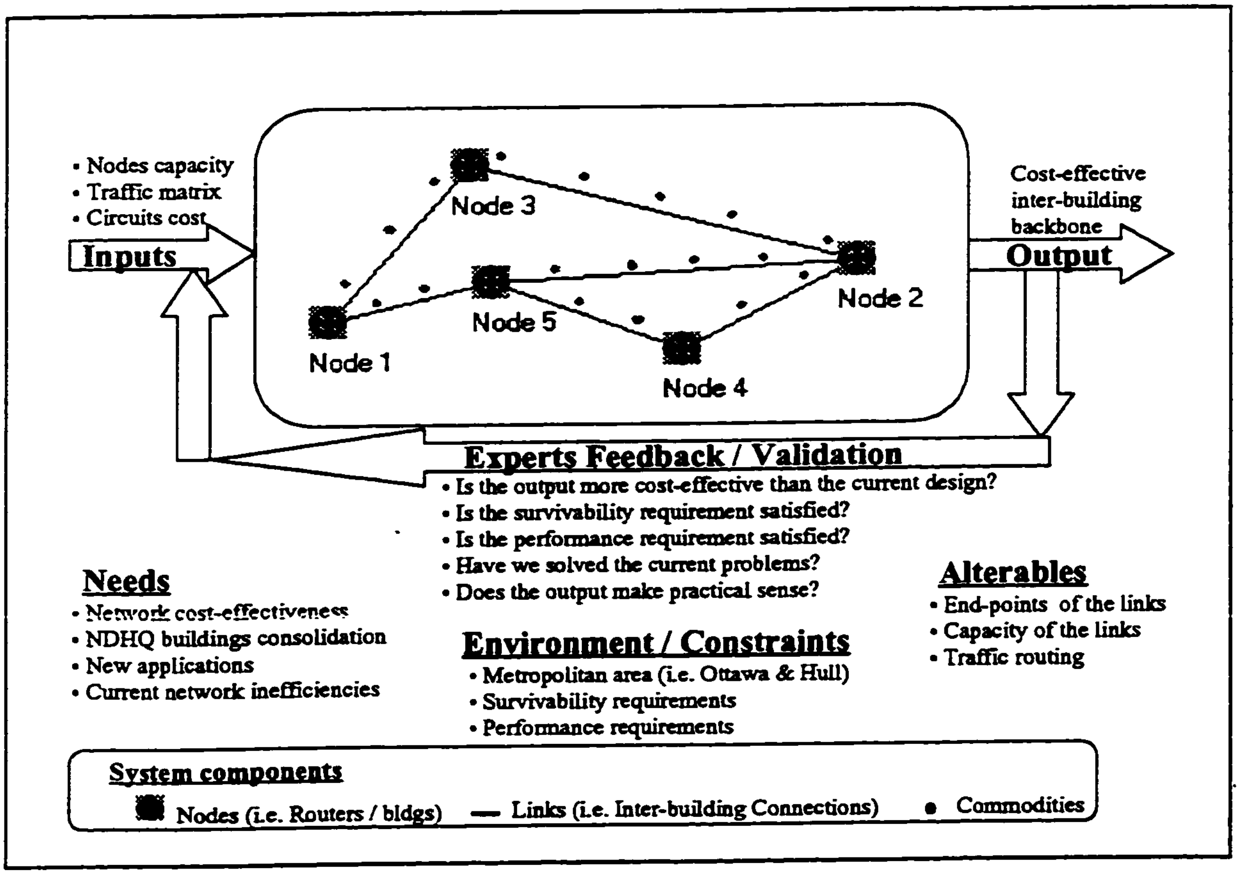

Figure 1-1: NDHQ MAN system overview

1.1. Background

Until 1992, leased lines were added between NDHQ buildings without centralised planning or configuration control. The increasing requirement to interconnect heterogeneous computer systems resulted in the need to engineer, design and implement a Metropolitan Area Network. This infrastructure had to be capable of accommodating any system and supporting NDHQ-wide internetworking requirements. As a result, the NDHQ MAN project was initiated, which involved the construction of the MAN Operations Centre (MANOC) to monitor, maintain and control the MAN [DCSEM 6-2-3, 1992].

By 1994, the MAN included 12 buildings interconnected with leased lines (T1 and 56kbps) [DISEM 2-2-5, 1994]. Since then, it has grown to 33 buildings and has recently gained external connectivity to the Defence Wide Area Network (DWAN)[1]. The baseline network counts some 42 routers, 296 servers and supports approximately 10,000 military and civilian personnel. Figure 1-2 illustrates the topology of the NDHQ MAN inter-building backbone at the time this thesis was initiated.

1.2. System components

There are three main components to the system: the nodes, the links and the commodities. This section provides a detailed description of each of these components and how they interact.

1.2.1. Commodities

The commodities are the "raison d'être" of a telecommunication network. They are, to telecommunication networks, what vehicles are to road networks and what letters are to postal networks. In other words, commodities in a telecommunication network are the actual goods that need to be transferred between points A and B. Just like mail, commodities are characterised by their origin, destination and size. These characteristics are key to this work, because they allow the model to ensure that commodities are continuously ***routed*** from origin to destination and that enough capacity is provided on the network links to support their ***transmission*** within an acceptable amount of time. Section 1.4.2. provides additional details on how the information on each commodity is organised as a traffic matrix.

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[1] The DWAN is a router-based Frame Relay network connecting all major bases and stations of the Department of National Defence/Canadian Forces (DND/CF) across Canada and internationally.

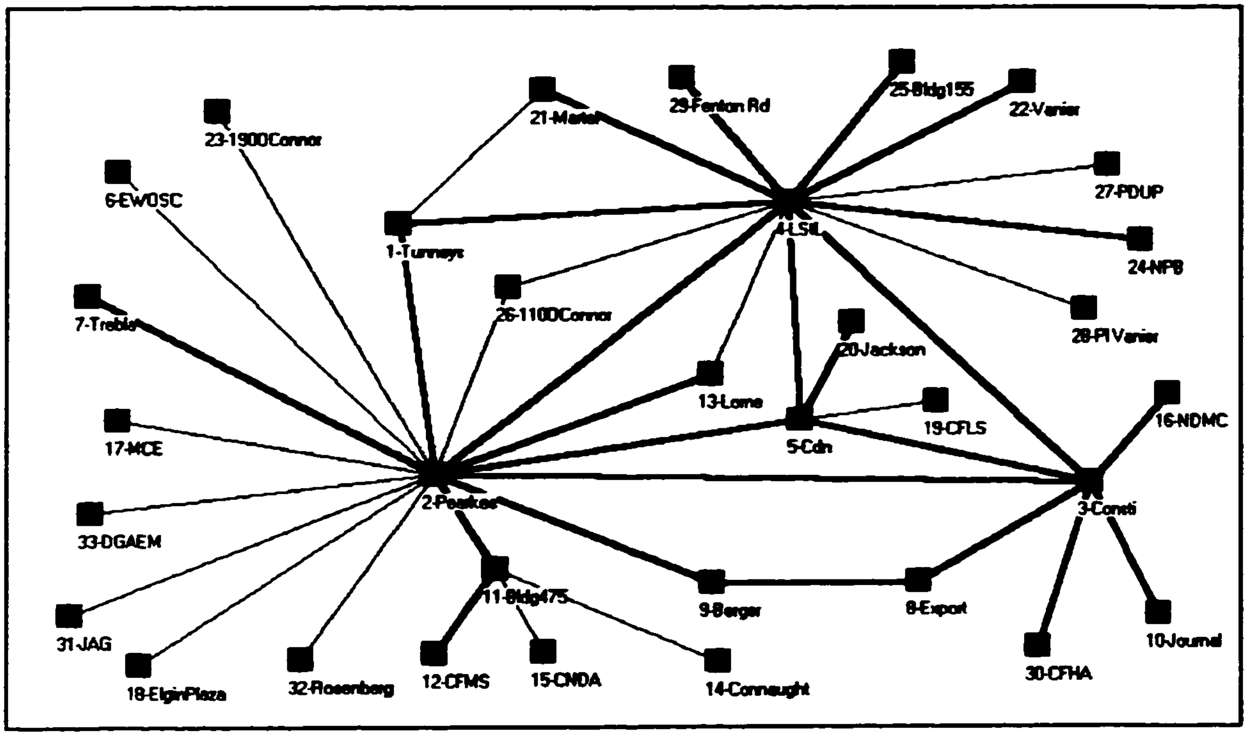


Figure 1-2: Baseline topology of the NDHQ MAN (15 May 1997)

Throughout this document, commodities will be referred to by their origin and destination nodes. Since commodities are directed, the order used to list the node names is important. For instance, Table 1-1 illustrates a possible path for Commodity "Node2-Node1", which corresponds to the commodity that has Node 2 and Node 1 as origin and destination respectively.

1.2.2. Nodes

The nodes can themselves be compared to a junction in a road network or a mail distribution centre of a postal network. As mentioned in Section 1.1., the problem under study is a router-based network. Therefore each node models one inter-building backbone router, which assumes that there is only one backbone router per building. Similarly to the road junction and the mail distribution centre, the node will have a physical location and a processing capacity. In a communication network, the node is where decisions are made in terms of where the traffic will go from there. From an inter-building backbone perspective, Table 1-1 summarises the three possible outcomes of a routing decision at a given node.

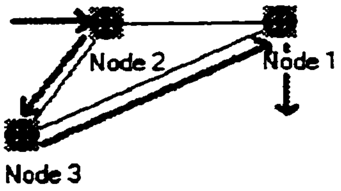
Outcome	Description	Example
1. Traffic Added	Traffic is added to the backbone from the underlying network of a given node (i.e. from the building's internal LANs). This node is referred to as the "Origin" node for this traffic.	 In this example, new traffic is added to the network through "Node 2", routed through "Node 3" and dropped at "Node 1", its destination.
2. Traffic Dropped	Traffic is dropped from the backbone into the underlying network of a given node. This node is referred to as the "Destination" node of this traffic.	
3. Traffic Forwarded	Traffic is simply routed through a given node. This node is referred to as a "Transit" node.	

Table 1-1: Possible outcomes of a routing decision

1.2.3. Links

The inter-building backbone of the MAN is a private network constituted of private lines. Private lines are transmission facilities that customers lease from a Telecommunications Service Provider (TSP) for their exclusive use. Because these lines are billed on a fixed rate (usage independent), it is potentially cheaper for an organisation to lease private lines between locations that need to exchange large amounts of traffic [Magnanti *et al*, 1995].

Just as a road capacity can be increased by increasing the number of lanes and/or the speed limit, the capacity of a link depends on the type and number of facilities installed on it. In telecommunications, facilities provide high bandwidth point-to-point connections, each of them transmitting information at different rates [Gendron *et al*, 1996]. In this problem, two types of facilities are considered, the DSA (Digital Signal Level A) which provides 56 Kbps of throughput and the DS1 (Digital Signal Level 1) which provides 1.544 Mbps.

Again, it is worth noting that links will be identified by their end points. For instance, in the example of Table 1-1, Link "Node1-Node3" connects Nodes 1 and 3. Since links are undirected, it does not matter which node is mentioned first.

1.3. System needs

The system needs are the motivations for tackling a given problem. The most significant factors motivating the redesign of the MAN are the consolidation of the NDHQ within fewer buildings, the expected implementation of several high bandwidth national applications across the MAN, several reported inefficiencies with the current MAN from an external consulting firm [Ma *et al*, 1998] and the constant economical pressures. These factors will be looked at in more detail in the following subsections.

1.3.1. NDHQ consolidation

As a direct consequence of downsizing in the Department of National Defence/Canadian Forces (DND/CF), a significant infrastructure project was initiated in 1997 to consolidate NDHQ within approximately 17 buildings by 1999/2000, from the current 33. It is important to note that this thesis was intended to coincide with this predicted end-state. With this mandate, the expected end-state of the consolidation project to 17 buildings was used throughout this thesis as the problem to solve.

1.3.2. Current network inefficiencies

The current MAN is highly meshed, which results in too many paths between building pairs. Consequently, asymmetric routing and other sub-optimal routings have been observed on the network [Ma *et al*, 1998]. Inherently, consolidating the NDHQ population within fewer buildings should alleviate these problems. In any case, the recommended design should consider the fact that a simple topology with high speed links is easier to manage and troubleshoot and potentially less expensive.

1.3.3. New applications

Several new national and regional applications with high bandwidth requirements will be implemented over the next few years and they will rely on the MAN to reach their clients. The implementation of these applications could have a significant impact on the traffic matrix of the network. Depending on where the client basis resides, for these applications, it may result that some inter-building links should be moved, added, or consolidated to improve transactions performance. These effects will need to be considered by the model.

1.3.4. Current economical climate

Nowadays, more than ever, cost-effectiveness is of paramount importance in project acceptance. Business case analysis techniques are used to ensure that the option selected makes the most business sense. The DND/CF make no exception to this reality and are under constant budgetary pressures just like any other government department or private industry who wants to remain competitive. It is therefore essential that the solution obtained be as cost-effective as possible.

1.4. System inputs

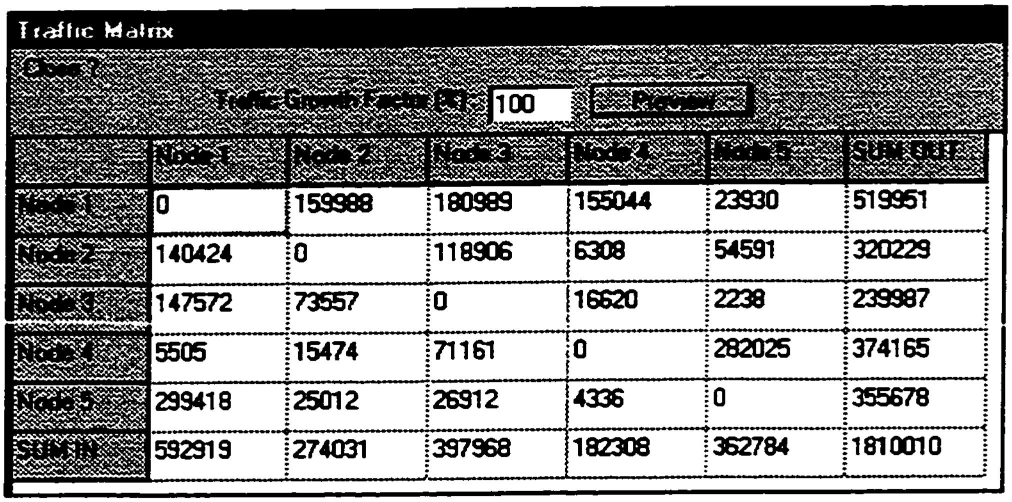
The system inputs correspond to those elements inherent to the problem solved and that can not be changed. This section only identifies the main system inputs initially identified in Figure 1-1. The additional inputs identified during the modelling phase will be described in Chapter 2. The details on how the specific data was obtained for all of these inputs is provided in Chapter 3.

1.4.1. Nodes capacity

Since we are interested in the total time required for a given commodity to be transmitted across the MAN (i.e. from origin node to destination node), the expected delays incurred on each link and node used by that commodity must be added up. In this problem, the intent is not to determine the capacity of each building router since the routers are already acquired and deployed. Therefore the properties of those routers, such as capacity, are taken as an input to the system.

1.4.2. Traffic matrix

Essentially, a traffic matrix identifies the traffic demands between every pair of nodes in the network. Figure 1-3 provides an example of a traffic matrix for a five-node network. The left column and top row identify the origin and destination nodes respectively. The details of how the NDHQ MAN traffic matrix was obtained are provided in Chapter 3.



Traffic Growth Factor (%): 100

	Node 1	Node 2	Node 3	Node 4	Node 5	SUM OUT
Node 1	0	159988	180989	155044	23930	519951
Node 2	140424	0	118906	6308	54591	320229
Node 3	147572	73557	0	16620	2238	239987
Node 4	5505	15474	71161	0	282025	374165
Node 5	299418	25012	26912	4336	0	355678
SUM IN	592919	274031	397968	182308	362784	1810010

Figure 1-3: Example of a traffic matrix (bps)

1.4.3. Link costs

The expected costs for installing and leasing each type of facilities are obviously key to this problem since we are interested in keeping design costs as low as possible. The cost of a private network is two-fold, the one-time installation cost, referred to as Service Charges, and the periodic leasing costs, referred to as Monthly Recurring Charges, of the facilities installed on the network. Therefore, the user incurs no costs based on utilisation of the links. The difference in price from one link to another will vary depending on the type and number of facilities installed and the distance between the locations that need to be connected. The first variation is quite obvious since, the more capacity is needed, the more expensive it will be. The second variation simply reflects the increased cost to the TSP of providing the service over a longer distance. Such tariff structure usually offers strong economies of scale. For instance, currently a DS1 circuit costs approximately the same as only 4 DSA circuits.

1.5. System environment & constraints

These elements correspond to the actual environment in which the system evolves and the important constraints imposed on it.

1.5.1. Metropolitan area

NDHQ's location in the Ottawa-Hull metropolitan area has advantages. For instance, it provides access to several TSPs, such as Bell Canada, Metronet Communications and Fonorola, which guarantees competitive prices. It also provides a large fibre optic infrastructure throughout the area with each key building having a point-of-presence from at least one service provider. Finally, having access to several TSPs also improves the survivability of the network since a failure or problem with one provider's infrastructure is unlikely to be replicated on another provider's infrastructure. There is therefore an obvious benefit to diversify one's portfolio among several TSPs.

1.5.2. Survivability requirements

The underlying concept of the NDHQ consolidation project is to regroup the majority of the headquarters within four core buildings and to distribute the remaining organisations in satellite buildings. As stated in the Service Level Commitment (SLC) [Ma *et al*, 1998], since the four core buildings are considered high availability buildings, survivability between the four core buildings must be insured. Survivability is the ability of a network to perform according to a specification after it has been damaged. Under certain assumptions, survivability means 100% reliability [Lloyd *et al*, 1995]. For a network to be considered survivable, it must satisfy the following two considerations:

- The ***physical topology*** of the network must be such that the traffic can be routed on an alternate path when a link fails. Since it is highly improbable that a second failure occurs before the first one is fixed, ensuring survivability against one failure is widely recognised as sufficient [Lloyd *et al*, 1995]. This means that their should be at least two disjoint physical paths between any two core buildings. Figures 1-4 illustrates an example of a non-survivable topology with four nodes and Figure 1-5 illustrates a counter-example. More specifically, in Figure 1-4, if Link "Node 1 - Node 3" fails, the network is broken in two sub-networks and Nodes 2 and 3 can not communicate with Nodes 1 and 4 until the failure is fixed, which is not acceptable between the four core buildings. In Figure 1-5, we can see that by adding a link between Nodes 2 and 4, no matter where a single-link failure occurs, the network will never be segmented.

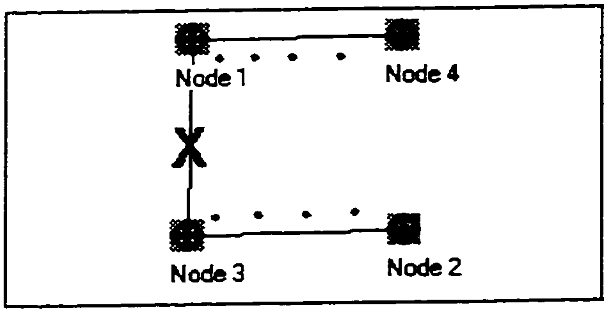


Figure 1-4: Example of a non-survivable topology

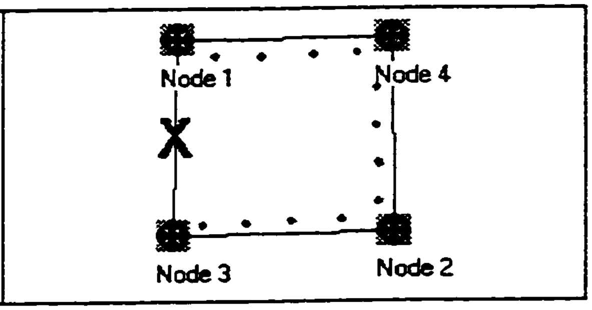


Figure 1-5: Example of a survivable topology

- It is not sufficient to ensure that there are at least two disjoint physical paths between any two core buildings. ***Spare capacity*** to accommodate the affected commodities must also be built-in the network to ensure that the network will continue to operate according to a specification under failure condition. Taking the example illustrated in Figure 1-5, if Commodity "Node1-Node3" is normally transmitted on Link "Node1-Node3", then spare capacity must be built in Links "Node1-Node4", "Node2-Node4" and "Node2-Node3" to support the additional traffic demand associated with this commodity under failure condition. This statement must be true for every commodity of the network and for every possible failure between the four core buildings. Of course, satisfying such requirements usually translates into a more expensive solution since it means more capacity on some links and potentially more links, as illustrated in Figure 1-5.

1.5.3. Performance requirements

Essentially, the performance requirement is a limitation on the allowable delay throughout the network. By carefully planning a network, one can ensure that sufficient spare capacity is provided such that the end-to-end delay throughout the network will never exceed a desired value. This value, as found in the SLC [Ma *et al*, 1998], includes the originator's local infrastructure, the inter-building backbone and the destination local infrastructure. For the purpose of this thesis, we are interested in the delay incurred on the inter-building backbone. Furthermore, this restriction applies to messages of any size and even under failure conditions.

1.6. Alterables

Essentially, the alterables correspond to those system elements that can be adjusted at solution time to directly influence the output. In this problem, the alterables are the end-points of the links, their respective capacity and the routing of the commodities on those links. All of these will have a direct influence on the cost, survivability and performance of the final solution.

1.6.1. End-points of the links

Carefully selecting the end-points (i.e. Nodes) of each link will have a significant impact on the total number of links required and therefore on the solution cost. Also, to ensure that all commodities can be routed continually from origin to destination at minimum cost, links end-points must be carefully selected.

1.6.2. Capacity of the links

There must be sufficient capacity in each link to ensure that all commodities can be routed on the network with acceptable performance under both normal and failure conditions. The capacity of a link depends on the number of facilities of each type installed on it (see Section 1.2.3). For example, if a link is constituted of two DS1, then its capacity is 3.088 Mbps.

1.6.3. Traffic routing

As discussed in Section 1.2.2., traffic routing refers to the allocation or distribution of the commodities on the network links. It defines which links should be part of the path that will connect the origin and destination nodes of each commodity. Such decision has a significant impact on the performance and cost of a network, because the longer a path the more important the delay will be and the shorter the paths the more links are required and the more expensive the solution will be.

1.7. System output

The output corresponds to the objective established for modelling the system. Using the terminology presented in this chapter, we are trying to achieve the following:

> "Based on the inputs, the alterables must be set such that the output is achieved and the needs and constraints are satisfied."

In most cases, there will be one overall objective and potentially several sub-objectives. By achieving the sub-objectives, the achievement of the overall objective is ensured. A very effective way to understand the objectives of a problem is to organise them in a hierarchical manner as illustrated in Figure 1-6.

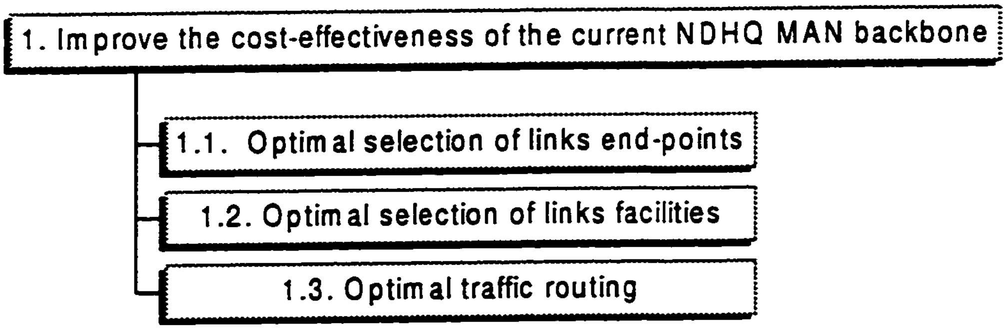


Figure 1-6: Objectives hierarchy

When considering the NDHQ MAN problem, the overall objective is to improve the cost-effectiveness of the current inter-building backbone. This objective will be achieved through simultaneous optimal selection of links end-points, links facilities and traffic routing on those links with respect to solution cost, performance and built-in survivability.

The accurate identification of the objectives is key to any problem, but the means of assessing their achievement are also very important. Objective measures are therefore required to validate the output of the system. They are summarised in the following questionnaire:

1. Is the design solution less expensive than the current design (need from Section 1.3.4.)?
2. Is the survivability requirement satisfied (constraint from Section 1.5.2.)?
3. Is the performance requirement satisfied (constraint from Section 1.5.3.)?

4. Have we solved the inefficiencies of the current network (need from Section 1.3.2.)?
5. Does the design solution obtained make practical sense?

If the answer is "yes" to all of the above, then the overall objective of the problem has been achieved.

The first objective measure can be verified using business case analysis techniques. More specifically, since we are dealing with one-time costs and periodic costs, a Net Present Value (NPV) of the costs for both the current network and the design solution can be used to determine the economical value of each solution. Their comparison will provide a confirmation as to whether or not the new design solution is less expensive than the current network design.

The second objective measure is two-fold. Because the survivability requirement is only for four nodes, the physical survivability of the network can be easily verified through visual inspection of the solution topology. Therefore, one would expect at least four links as illustrated in Figure 1-5. The spare capacity provisionning would require a thorough analysis of the routes and expected performance of all commodities under all required single-link failure scenarios. In practice, this task needs to be supplemented by a simulation of possible failures to provide additional confidence that sufficient spare capacity has been built-in the network, a step beyond the scope of this thesis.

The third objective measure is relatively straightforward to verify with a few calculations. Based on the traffic routing and links capacity of the design solution, one can obtain the utilisation of each link and derive and expected delay for that link. The expected end-to-end delay for a given commodity can then be obtained by summing all the delays of the links and nodes along the path taken by that commodity. These calculations will be covered in more detail in Chapter 2. Again, further validation of the performance of the solution could be achieved using a network simulation tool.

The fourth objective measure is meant to confirm whether or not the current inefficiencies of the MAN described in Section 1.3.2., have been eliminated or reduced to an acceptable level.

Finally, the fifth objective measure is more difficult to verify than the other ones as it either requires simulation or live testing. A review from the network operators may also provide useful insights.

Chapter 2

Model development

Network design problems offer a major challenge to the telecommunication industry and correspondingly, a fair amount of work has been accomplished in terms of research and development in the area of network design optimisation. These methods and algorithms are tools available to telecommunications network planners and designers when making important design recommendations. In addition, most of the methods and algorithms used in this field can be applied to several other planning activities such as facility location, production planning and transportation [Magnanti *et al*, 1993].

As a result of the problem definition completed in Chapter 1, we now have all the fundamental elements required to develop the mathematical formulation of the model. First, in Section 2.1. a qualitative expression of the optimisation model is provided. The following two sections summarise the literature review and formulation development necessary to obtain the final formulation of the model. Section 2.4. summarises the complete mathematical formulation of the model and Section 2.5. provides some problem size calculations. The reader is referred to Appendix A for additional explanations on some of the terminology presented in this chapter.

2.1. Generic system model

Using the elements presented in Chapter 1, a generic model of the system can be obtained. The intent of this model, summarised in Figure 2-1, is to put in words what will later be expressed quantitatively. The objective is to simultaneously minimise the design cost of the solution and to keep the length of the commodities' route as short as possible within the optimal links configuration. This is achieved through simultaneous optimal selection of the end-points of the links, the type and number of facilities installed on each link and the allocation of the traffic flows on the links. Yet, the survivability and performance requirements must be satisfied.

2.2. Literature review

In this section, a review of the literature is presented. The intent of this review was to get an appreciation of the type of work that has been accomplished in this field and identify existing

Minimise

- NPV of the solution costs; and
- Length of the commodities' routes.

With respect to

- The end-points of the links;
- The type and number of facilities installed on each link; and
- The route of each commodity.

Subject to

- Satisfying the survivability requirements; and
- Satisfying the performance requirements;

Figure 2-1 – Generic system model

modelling elements that could be used to formulate and solve the problem under study. Several related papers have been reviewed, but only those that have influenced the formulation of this problem will be presented. The review is organised by category according to the requirements of the problem.

2.2.1. Capacity and flow distribution

Gendron *et al* [1996] provide a comprehensive survey of models and algorithms for multi-commodity Capacitated Network Design Problems (CNDP) as encountered in the telecommunication industry. A key element mentioned in the article is that capacitated network design problems are notoriously difficult to solve, unlike their uncapacitated counterparts, mainly because the Linear Program (LP) relaxation of multi-commodity flow formulations generally does not provide tight lower bounds. In addition, the LPs of these formulations are highly degenerate, which makes their solution by the simplex method unattractive. As an illustration, they refer to the well-known Minimum Spanning Tree (MST) problem. The uncapacitated version of the problem is easily solved by greedy algorithms, while the capacitated version, which is *NP*-hard, is very difficult to solve in practice. For an illustration of the uncapacitated MST using Prim's algorithm [Prim, 1957], see Section 4.2 of Appendix B. The conclusion of this paper supports that solving efficiently some of these difficult problems might require a judicious combination of cutting planes, Lagrangean relaxation and sophisticated heuristics.

A solution to the Two-Facility Loading Problem (TFLP) was reviewed [Magnanti *et al*, 1995]. Essentially, the TFLP is the two-facility version of the CNDP presented by Gendron *et al* [1996]. The objective of the TFLP is to simultaneously assign capacities to arcs and select the single route to be used by each commodity. Solving this problem addresses the core requirements of the NDHQ MAN problem. Thus, the formulation proposed in this article forms the basis for the formulation developed to solve the NDHQ MAN problem. After verifying that the TFLP is strongly *NP*-Hard, the authors consider two solution approaches, the first one based on Lagrangean relaxation, which has shown a significant improvement on the lower bound upon the LP relaxation bound. The second approach is based on strong cutting planes techniques and appears to be an effective algorithmic tool to solve problems of the size that arise in the telecommunication industry.

Magnanti *et al* [1993] focus on the single origin-destination design problem with up to three capacitated facilities. One of the key results of this paper is the demonstration that the single facility and certain "common breakeven point" versions of the two-facility and three facility loading problems are polynomially solvable as a shortest path problem.

Another issue that had to be addressed was modelling the routing mechanism used by the MAN routers. Since the routers on the MAN route traffic based on the Open Shortest Path First (OSPF) protocol, the first logical step was to review the OSPF standard [Moy, 1994]. In essence, the OSPF protocol routes traffic such that the selected path (or route), for a given commodity, will always be the one generating the least delay. The following are characteristic performances produced by the protocol:

- When several routes to a destination have an equal cost, traffic is distributed equally among them.
- OSPF is a link state routing protocol as opposed to a distance vector routing protocol. This means that OSPF makes a routing decision based on the metrics associated with each link of the network, which is directly related to the speed and utilisation of that link.
- OSPF recalculates routes quickly in the face of topological changes (e.g. link failure), utilising a minimum of routing protocol traffic.
- Each router builds a routing table based on the shortest path tree calculated, with Dijkstra's algorithm [1959], using itself as the root.

It was then necessary to look for existing shortest path models which could potentially be integrated in the overall NDHQ MAN model. In its most basic form, the objective of the shortest path problem is to minimise the sum of the costs associated with the links selected to connect the origin to the destination [Ahuja *et al*, 1993]. In the case of OSPF, the cost associated with a link is inversely proportional to its capacity. Section 2.3. provides more details on how this component was integrated in the formulation of the model.

2.2.2. Survivability considerations

Lloyd *et al* [1995] address the problem of designing Minimum Cost Survivable Networks (MCSN), also categorised as an *NP*-hard problem. Formulations for both the node-disjoint and path-disjoint networks are presented and a solution approach based on a system of heuristics for the node-disjoint problem is described. The problem covered in these papers is limited to the design of the physical topology and therefore does not address the need for spare capacity.

Alevras *et al* [1997] present a survey of the models developed for network survivability over the last ten years and categorise them according to their corresponding restoration strategies. As such, three survivability models are presented: a diversification, a reservation and a re-routing of affected demands model. Similarly, Van Caenegem *et al* [1997] present three survivability models for three different restoration strategies in a mesh network, in the case of a single link failure: link restoration, path restoration and link disjoint route. These two papers propose sufficient modelling elements for spare capacity planning to satisfy the requirements of the NDHQ MAN problem. It is important to note that these models cover both the "physical topology" and "spare capacity" aspects of survivability.

2.2.3. Performance considerations

A review of traffic engineering fundamentals [Spohn, 1997] addressed the performance requirement of the problem (i.e. end-to-end delay). It provided an adequate specification of link and node utilisation based on the M/M/1 queuing model.

2.3. Formulation development

Table 2-1 provides the notation, including names of sets, variables and parameters used throughout this chapter. The formulation developed in this section is sufficiently complex to warrant a modular introduction. In the following paragraphs, a detailed description of the key building blocks of the model's mathematical formulation is presented.

Sets

$G(N_s, A_s)$	Network Graph composed of N_s nodes and A_s arcs with the network in state s.
S	Set of all possible network states.
N_s	Set of all operational nodes with the network in state s.
$A_s(U)$	Set of all <u>undirected</u> operational arcs (i,j) in a connected network graph of N_s nodes.
$A_s(D)$	Set of all <u>directed</u> operational arcs (i,j) in a connected network graph of N_s nodes.
L	Set of all facilities available for arcs sizing.
K_s	Set of all commodities with the network in state s.

Variables

x_{ij}	Topology design variables; $x_{ij} = 1$, if the <u>undirected</u> arc (i,j) exists and $x_{ij} = 0$ otherwise.
y_{ij}^l	Arc sizing variables: they define the number facilities, of type $l \in L$, loaded on the <u>undirected</u> arc (i,j).
f(s,ij,k)	Arc flow variables: they define the flow of commodity k on arc (i,j) in the <u>direction</u> i to j, with the network in state s (in bps).

Parameters

ir	Interest rate per month
ph	Planning horizon in months.
α	Weight of cost factor; $0<\alpha<1$ in objective function.
$orig_k$	Origin of Commodity k.
$dest_k$	Destination of Commodity k.
dem_k	Demand for Commodity k.
δ_k^s	Reservation parameter: the proportion of dem_k that must be satisfied when the network is in state s.
fc_l	Facility capacity: the capacity multiplier (in bps) for facility of type l.
sc^l	Service charges: the one-time cost of installing one facility of type l (distance independent).
mrc_{ij}^l	Monthly recurring charges: the recurring cost of leasing one facility of type l between nodes i and j.
ad_{ij}	Maximum acceptable average arc delay (considers waiting time in the node's buffer and the transmission time on link ij).
nd_i	Maximum acceptable average node delay (considers waiting time in the node's buffer and the processing time at node i).
nc_i	Node capacity in packets per second (pps)
ps	Average packet size in bits.
npv_{ij}^l	Net Present Value of the cost of installing one facility of type l on link ij.
M	Large positive number.

Nomenclature

Set	One capital letter (e.g. L)
Variable	One minuscule letter (e.g. x)
Parameter	A word or abbreviation in small letters (e.g. dem) or a greek letter (e.g. δ)

Table 2-1 – Sets, variables and parameters

2.3.1. The TFLP

A fundamental building block of the final formulation is the TFLP from Magnanti *et al* [1995] generalised to support multiple facilities as illustrated in Figure 2-2. Since this model does not take survivability requirements into account, the s introduced in table 2-1 were left out for simplification. The objective function (1) minimises the total service cost of the solution. In other words, it minimises the sum of the one-time installation costs of all the facilities required. The first set of constraints (2) ensures continuous end-to-end flow of the commodities. The second set of constraints (3) ensures that sufficient facilities will be installed on each arc to support all the commodities routed on those arcs. Finally, the last two sets of constraints identify the arc sizing variables as general positive integers (4) and the flow variables as real positive variables (5).

$$Min \quad \sum_{l\in L}\left[sc^{l} \sum_{(i,j)\in A(U)} y^{l}_{ij} \right] \qquad (1)$$

Subject to

- Flow conservation constraints:

$$\sum_{j\in N|(j,i)\in A(D)} f(ji,k) - \sum_{j\in N|(i,j)\in A(D)} f(ij,k) = \begin{cases} -dem_k & i = orig_k \\ dem_k & i = dest_k \\ 0 & \text{otherwise} \end{cases}$$

$$\forall\, i \in N, \forall\, k \in K \qquad (2)$$

- Links capacity constraints:

$$\sum_{l\in L} fc_l\, y^{l}_{ij} - \sum_{k\in K} f(ij,k) - \sum_{k\in K} f(ji,k) \geq 0 \qquad \forall\, (i,j) \in A(U) \qquad (3)$$

- Integrality and non-negativity constraints:

$$y^{l}_{ij} \geq 0 \text{ and integer} \qquad \forall\, (i,j) \in A(U), \forall\, l \in L \qquad (4)$$

$$f(ij,k) \geq 0 \qquad \forall\, (i,j) \in A(D), \forall\, k \in K \qquad (5)$$

Figure 2-2 – Generalised TFLP formulation

2.3.2. Survivability requirement

The spare capacity model used will depend on the network restoration strategy under failure conditions. OSPF, the routing protocol implemented on the NDHQ MAN dictates how the affected commodities will be re-routed on the network links. The way OSPF works, is that at short intervals, every router sends "Hello" packets on its interfaces to either establish new or maintain existing neighbour relationships. The smaller the intervals, the faster topological changes will be detected, but more OSPF routing protocol traffic will ensue. Upon discovery of a topological change such as a router interface failure, each router constructs a new tree of shortest paths with itself as the root. For a more detailed overview of the OSPF routing protocol, the reader is referred to Appendix C.

The reservation strategy described by Alevras *et al* [1997] appropriately models the restoration scheme of the OSPF protocol. With this strategy, the network designer has to specify the reservation parameter (δ_k^s) for every commodity. This model also takes into account all possible states of the network, numbered by s. When s=0, the network is fully operational, but s>0 means that one network component has failed. As a result, solving each possible state of the network constitutes an entirely new flow allocation problem.

The possible failure states and their related demand requirements influence Equations (2) and (3) as shown in Equations (6) and (7) of Figure 2-3. This modification increases the number of constraints significantly. See Section 2.5. for more details on the model size calculations.

- **Flow conservation constraints:**

$$\sum_{j \in N_s | (j,i) \in A_s(D)} f(s,ji,k) - \sum_{j \in N_s | (i,j) \in A_s(D)} f(s,ij,k) = \begin{cases} -\delta_k^s \cdot dem_k & \mathrm{i} = orig_k \\ \delta_k^s \cdot dem_k & \mathrm{i} = dest_k \\ 0 & \text{otherwise} \end{cases}$$

$$\forall \mathrm{s} \in \mathrm{S} \setminus \{0\}, \forall \mathrm{i} \in \mathrm{N_s}, \forall \mathrm{k} \in \mathrm{K_s} \quad (6)$$

- **Capacity constraints:**

$$\sum_{l \in L} fc_l y_{\mathrm{ij}}^l - \sum_{k \in K_s} f(s,ij,k) - \sum_{k \in K_s} f(s,ji,k) \geq 0 \qquad \forall \mathrm{s} \in \mathrm{S} \setminus \{0\}, \forall (\mathrm{i},\mathrm{j}) \in \mathrm{A_s(U)} \quad (7)$$

Figure 2-3 – Survivability formulation

2.3.3. Performance requirements

The intent of this subsection is to detail the approach taken to incorporate the End-To-End Delay Requirement (ETEDR) in the model. The following paragraphs first provide the fundamentals from queuing theory and then describe both, the link and node performance models. Finally, Section 2.3.3.4. explains how these two models were linked to ensure that the ETEDR is satisfied.

2.3.3.1. The M/M/1 model [Spohn, 1997]

Recalling the M/M/1 queuing model, lets define λ as the average arrival rate, μ as the service rate and ρ as the utilisation of the server. The following formula governs the relationship between these variables:

$$\rho = \frac{\lambda}{\mu} \tag{8}$$

The other important result needed from the M/M/1 model is the relationship between delay and utilisation. The average delay D equates to the sum of the waiting time T_w and the service time T_s, which can be further expressed as a function of the utilisation ρ:

$$D = T_w + T_s = \frac{T_s}{1-\rho} \tag{9}$$

Since the service time T_s is the inverse of the service rate μ, Equation (9) can be expressed as follows:

$$D = \frac{1/\mu}{1-\rho} \tag{10}$$

Substituting Equation (8) in (10), yields:

$$D = \frac{1}{\mu - \lambda} \tag{11}$$

2.3.3.2. Arc capacity constraints

In this context, we model an arc as a server (see Figure 2-4). In this model, traffic is queued in the buffer of the transmitting node, until the arc (i.e. the server) becomes available to transmit that traffic. The queuing discipline is First-In-First-Out (FIFO), which is how OSPF operates when the Type Of Service (TOS) option is not enabled. Therefore the mean delay mad_{ij} incurred to transmit bits of traffic on Arc (i,j) can be expressed as follows, based on Equation (9):

$$mad_{ij} = T_w + T_s \tag{12}$$

where T_s becomes the transmission time over the link and T_w becomes the queuing time in the buffer of the transmitting node.

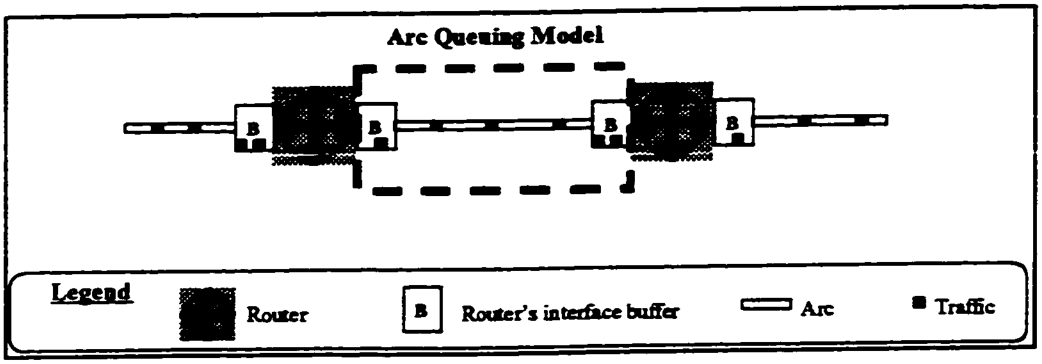


Figure 2-4 — Arc queuing model

In the case of communication networks, arrivals correspond to the arrival of traffic flow and service rate corresponds to a line rate or a node capacity. Therefore, defining C_{ij} as the capacity of arc (i,j) and F_{ij} as the total flow of traffic transmitted over Arc (i,j) in both directions, Equation (11) becomes:

$$mad_{ij} = \frac{1}{C_{ij} - F_{ij}} \tag{13}$$

As currently expressed, mad_{ij} represents the mean delay in seconds for one bit since C_{ij} and F_{ij} are in bits per second (bps). Delay is more meaningful in seconds per packet and a simple re-scaling defines the mean delay mad_{ij} to transmit entire packets over Arc (i,j). Now suppose the maximum acceptable average delay is ad_{ij} then we must have:

$$mad_{ij} = \frac{ps}{C_{ij} - F_{ij}} \leq ad_{ij} \tag{14}$$

Rearranging the terms, this can be rewritten as:

$$C_{ij} - F_{ij} \geq \frac{ps}{ad_{ij}} \tag{15}$$

By substituting the exact expressions for C_{ij} and F_{ij} in Relation (15) and noting that (15) applies only when link (i,j) is implemented, we obtain the following link capacity constraint:

$$\boxed{\sum_{l \in L} fc_l y_{ij}^l - \sum_{k \in K_s} f(s,ij,k) - \sum_{k \in K_s} f(s,ji,k) - \left(\frac{ps}{ad_{ij}}\right) x_{ij} \geq 0 \qquad (16)}$$

To summarise, Equation (16) provides a mean of satisfying a certain maximum average arc delay limitation (ad_{ij}) and considers the statistical advantage of multiplexing several facilities as a single link. Equation (16) also carries an important computational cost, since it requires the addition of a set of binary variables to ensure that performance requirements are only enforced on existing links (i.e. $x_{ij} = 1$). Using Equation (10), Figure 2-5 was generated to illustrate the effects of requiring a certain delay limitation on a given link upon its utilisation, for several links capacity.

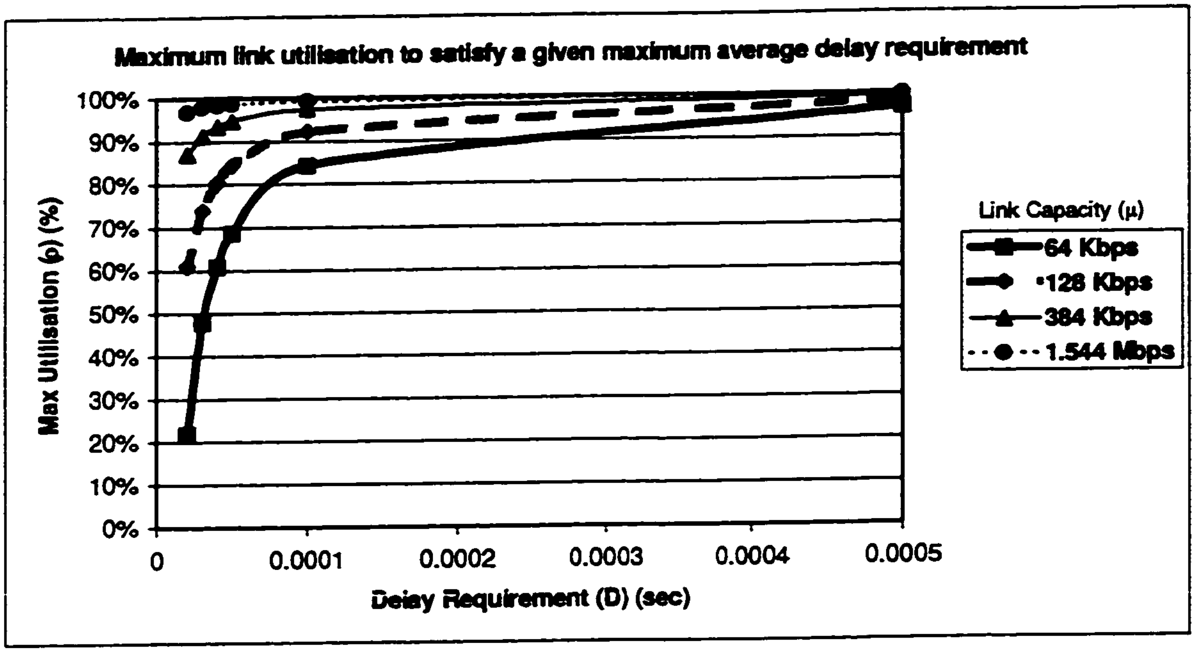


Figure 2-5 – Link utilisation-delay relationship

2.3.3.3. Node capacity constraints

In this context, we model a node as the server (see Figure 2-6). In this model, traffic is queued in the buffer of the processing node until it becomes available to process the next packet in line. Therefore the mean delay mnd_i incurred to process bits of traffic at node i, can be expressed as follows, based on Equation (9):

$$mnd_i = T_w + T_s \qquad (17)$$

where T_s becomes the processing time through the node and T_w becomes the queuing time in the node's buffer.

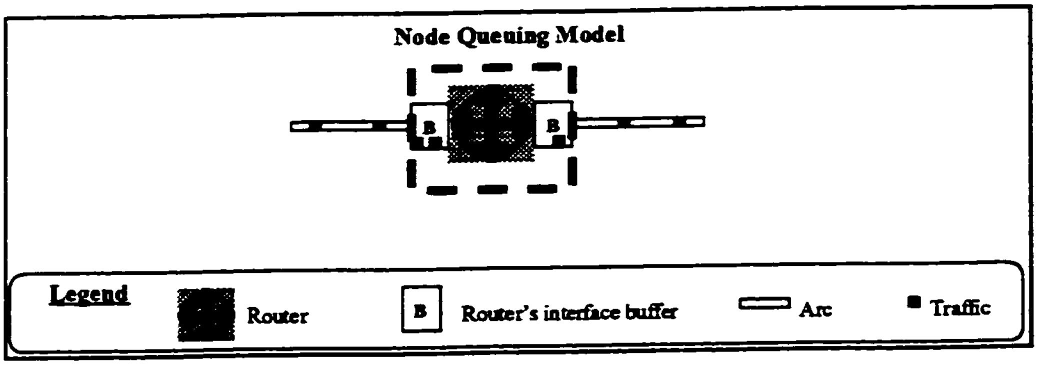
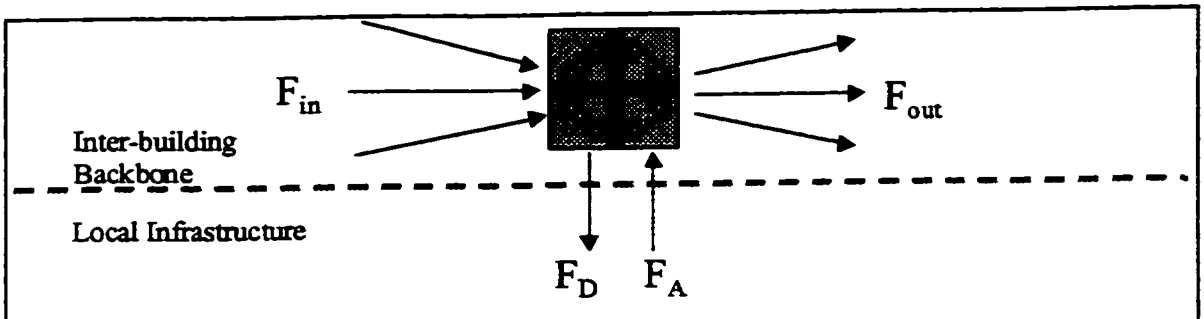


Figure 2-6 – Node queuing model

In the case of a node, we need to carefully determine the value of the service rate μ and arrival rate λ involved in Equation (11). The service rate is rather straightforward, since every node i has a processor capacity nc_i in packets per seconds (pps), which is a measure of the service rate of the node. The arrival rate, on the other hand, is the amount of flow requiring processing by the node. Figure 2-7 illustrates the different flows involved in the loading of a node.



Where:

- F_{in} represents the sum of all external incoming flows to a given node;
- F_{out} represents the sum of all external outgoing flows from that node;
- F_D represents the sum of the external flows arriving to destination and being Dropped into the local infrastructure of that node, and
- F_A represents the sum of the local flows originating from this node and being Added to the external outgoing flows.

Figure 2-7 – Traffic flows distribution at a given node

Based on Figure 2-7, a flow conservation equation is:

$$F_{in} + F_A = F_{out} + F_D \tag{18}$$

Since either side of Equation (18) is a measure of the amount of traffic that needs to be processed at that node, we can use whichever is easier to calculate and substitute it in Equation (11) to get:

$$mnd_i = \frac{1}{nc_i - (F_{in} + F_A)} \tag{19}$$

Currently, nc_i and mnd_i are expressed in packets per second, while F_{in} and F_A are in bits per second. Since delay is more meaningful in seconds per packet, a simple re-scaling is therefore required to modify Equation (19). Suppose the maximum acceptable average delay is nd_i, then we must have:

$$mnd_i = \frac{ps}{ps \cdot nc_i - (F_{in} + F_A)} \leq nd_i \tag{20}$$

Rearranging the terms, this can be rewritten as:

$$F_{in} \leq ps \cdot \left(nc_i - \frac{1}{nd_i} \right) - F_A \tag{21}$$

By substituting the exact flows expressions in Relation (21, we obtain the following node capacity constraint:

$$\boxed{\sum_{k \in K} \sum_{j \in N} f(s, ji, k) \leq \mathrm{ps} \cdot \left(nc_i - \frac{1}{nd_i} \right) - \sum_{k \in K | i = orig_k} dem_k} \tag{22}$$

Equation (22) provides a mean of satisfying a certain maximum node delay limitation (nd_i). For the NDHQ MAN problem, the nodes capacity nc_i are known. In a node capacity sizing problem, the parameters nc_i would be considered as variables and the model could be used to simultaneously determine the optimal capacity of the nodes.

2.3.3.4. End-To-End Delay Requirement (ETEDR)

The problem is to adequately size nd_i and ad_{ij} such that the ETEDR for every commodity k is satisfied. The simple solution to keep Equations (16) and (22) linear is to manually pre-assign maximum average delay value for all nodes (nd_i) and arcs (ad_{ij}) before the solution process. In this case, all nodes have the same delay limitation parameter and the same applies to the links as shown in Equations (23) and (24) respectively:

$$\mathrm{nd}_i = \mathrm{nd} \quad \forall\, i \in N_s \tag{23}$$

$$\mathrm{ad}_{ij} = \mathrm{ad} \quad \forall\, ij \in A_s(U) \tag{24}$$

As a result, the following relation can be used to govern the relationship between nd, ad and ETEDR:

$$(R+1)\cdot \mathrm{nd} + R \cdot \mathrm{ad} \leq \mathrm{ETEDR} \tag{25}$$

where R is the expected maximum number of hops (i.e. number of links) between any commodity's origin and destination.

2.3.4. OSPF consideration

With OSPF, the metrics assignment to each interface (or link) is inversely proportional to its throughput (bps). In other words, the faster the interface, the lower its metric and therefore the more traffic will be routed via that interface. The objective is therefore to minimise the traffic flow transmitted on those expensive links (i.e. low capacity) and maximise the traffic flow transmitted on those less expensive links (i.e. higher capacity). This corresponds to the shortest path problem solved as part of the OSPF routing algorithm. Equation (26) illustrates these additional non-linear objective functions (one per commodity per network state) using the default OSPF interface metric.

$$Min \sum_{(i,j)\in A_s(D)} \left(f(s,ij,k) \cdot \sum_{l \in L} \left({10^8} \Big/ {fc_l \, y^l_{i\wedge j\; i\vee j}} \right) \right) \qquad \forall\, s \in S, \forall\, k \in K_s \tag{26}$$

One solution to avoid this non-linear component in the objective function is to minimise the total amount of traffic throughout the network. As a result, the model will attempt to keep the paths as short as possible. It is important to note that the intent of this model component is not to minimise the expected total amount of traffic with a differentiation between network states, but rather to minimise the total amount of traffic across the network for all network states. In other words the probability of being in state s is not relevant to this exercise as flow distributions across the network in a given state will have no impact on the flow distribution in an other network state. Therefore, Equation (26) is simplified to the following:

$$Min \sum_{s\in S} \sum_{(i,j)\in A_s(D)} \sum_{k \in K_s} f(s,ij,k) \tag{27}$$

2.3.5. Total cost consideration

To justify an investment of the size of the NDHQ MAN, it is important that the recommended decision reflect the planning horizon of the problem. Since all the facilities are leased, the periodic charges associated with these leases need to be taken into account. The solution is to calculate the Net Present Value (NPV) of all costs associated with the design solution recommended over a predetermined planning horizon. In this case, for a given link (i,j) and facility l we have a one time initial charge (sc_l) and a series of uniform end-of-period payments (mrc_{ij}^{l}). Using the well-known NPV formula, for periodic end-of-period payments, the corresponding objective function term would be:

$$\mathrm{npv}_{ij}^{l} = sc^{l} + mrc_{ij}^{l}\left(\frac{(1+ir)^{ph}-1}{ir(1+ir)^{ph}}\right) \quad . \tag{28}$$

where *ir* is the interest rate per month and *ph* is the planning horizon also in months.

2.4. Complete formulation

The integration of all these components as a link-based Mixed-Integer/linear Programming (MIP) formulation can now be accomplished. Figure 2-8 summarises the final formulation proposed in this thesis. Equation (29), a multi-objective function, minimises a linear combination of the NPV of the total network costs (sc and mrc) and of the total amount of flow circulating on the network. Depending on the user's preference, the emphasis on either one of the components can be adjusted through the weight α.

Equation (30) ensures flow conservation of the commodities under all possible operational states of the network. The designer has the flexibility to adjust the amount of spare capacity planned in case of a failure by adjusting the reservation parameter δ_k^s, which corresponds to the proportion of traffic demand for commodity k that needs to be supported under state $s \in S$.

Relations (31) and (32) are the two sets of constraints that enforce performance requirements. More specifically, by carefully setting the total capacity and flows on each link, Constraint (31) ensures that the utilisation of the links remains acceptable under every possible network state. Similarly, by carefully allocating traffic flows across the network, Constraint (32) ensures that the utilisation of each node is kept at an acceptable level.

Relation (33) ensures that facilities can only be loaded on selected links. It is important to note that the left hand side of Relation (33) can be eliminated when performance requirements are considered in the formulation (i.e. when ps / $ad_{ij} > 0$ in Constraint (31)). Finally, Relations (34), (35) and (36) ensure that the decision variables correspond to realistic choices.

$$Min \;\; \alpha\left[\sum_{l\in L}\sum_{(i,j)\in A_0(U)} npv_{ij}^{l}\cdot y_{ij}^{l}\right] + (1-\alpha)\left[\sum_{s\in S}\sum_{(i,j)\in A_s(D)}\sum_{k\in K_s} f(s,ij,k)\right] \qquad (29)$$

Subject to

- Flow conservation constraints:

$$\sum_{j\in N_s|(j,i)\in A_s(D)} f(s,ji,k) - \sum_{j\in N_s|(i,j)\in A_s(D)} f(s,ij,k) = \begin{cases} -\delta_k^s\cdot dem_k & \mathrm{i}=orig_k \\ \delta_k^s\cdot dem_k & \mathrm{i}=dest_k \\ 0 & \text{otherwise} \end{cases}$$

$$\forall\, \mathrm{s}\in \mathrm{S}, \forall\, \mathrm{i}\in \mathrm{N_s}, \forall\, \mathrm{k}\in \mathrm{K_s} \qquad (30)$$

- Performance constraints:

$$\sum_{l\in L} fc_l\, y_{\mathrm{ij}}^{l} - \sum_{k\in K_s} f(s,ij,k) - \sum_{k\in K_s} f(s,ji,k) - \left(\frac{\mathrm{ps}}{ad_{\mathrm{ij}}}\right)x_{\mathrm{ij}} \ge 0$$

$$\forall \mathrm{s}\in \mathrm{S}, \forall\, (\mathrm{i},\mathrm{j})\in \mathrm{A_s(U)} \qquad (31)$$

$$\sum_{k\in K}\sum_{j\in N} f(s,ji,k) \le \mathrm{ps}\cdot\left(nc_{i} - \frac{1}{nd_{\mathrm{i}}}\right) - \sum_{k\in K|i=orig_k} dem_k \qquad \forall \mathrm{s}\in \mathrm{S}, \forall \mathrm{i}\in N_s \qquad (32)$$

- Facilities constraints:

$$x_{ij} \le \sum_{l\in L} y_{ij}^{l} \le M\, x_{ij} \qquad \forall\, (\mathrm{i},\mathrm{j})\in \mathrm{A_0(U)} \qquad (33)$$

- Integrality and non-negativity constraints:

$$x_{ij} = 0 \text{ or } 1 \qquad \forall\, (\mathrm{i},\mathrm{j})\in \mathrm{A_0(U)} \qquad (34)$$

$$y_{ij}^{l} \ge 0 \text{ and integer} \qquad \forall\, (\mathrm{i},\mathrm{j})\in \mathrm{A_0(U)}, \forall\, \mathrm{l}\in \mathrm{L} \qquad (35)$$

$$f(s,ij,k) \ge 0 \qquad \forall\, \mathrm{s}\in \mathrm{S}, \forall\, (\mathrm{i},\mathrm{j})\in \mathrm{A_s(D)}, \forall\, \mathrm{k}\in \mathrm{K_s} \qquad (36)$$

Figure 2-8 — Complete formulation

2.5. Problem size calculations

The last section of this chapter provides some insight into the size of the problem. It pinpoints the importance of each component of the formulation. In practice, manual and/or automated elimination can be done to significantly reduce the size of the problem. This elimination process performed prior to the solution of the problem is referred to as pre-processing and the one designed for the NDHQ MAN problem is described in Chapter 3. Figure 2-9 summarises the equations used to calculate the size of each component of the final formulation without pre-processing. Table 2-2 provides examples of problem size calculations based on the equations presented in Figure 2-9. The column numbers represent the equation numbers as described in Figure 2-8. This table clearly shows the impact of adding even a limited number of survivable nodes to the network. The survivable nodes are the nodes for which double paths and spare capacity must be planned and the survivable links are all possible links between these survivable nodes. Different scenarios with the NDHQ MAN problem are highlighted in grey.

	Number of constraints generated
(29) Objective Function	1
(30) Flow Conservation	$\left(\frac{nsn(nsn-1)+2}{2}\right)(nn(nn-1))+\left(nsn\,(nn-1)^2\,(nn-2)\right)$
(31) Links Performance	$\left(\frac{nsn(nsn-1)+2}{2}\right)\left(\frac{nn(nn-1)}{2}\right)-1+\left(\frac{nsn(nn-1)(nn-2)}{2}\right)$
(32) Nodes Performance	$\left(\frac{nn\cdot nsn(nsn-1)}{2}\right)+nn+nsn(nsn-1)$
(33) Facilities	$nn(nn-1)$
	Number of variables generated
(34) x_{ij} Binary	$nn(nn-1)/2$
(35) y^{l}_{ij} Positive Integer	$nl\cdot nn(nn-1)/2$
(36) $f(s,ij,k)$ Positive Real	$\left(nn(nn-1)\right)^2\left(nsn+\frac{nsn(nsn-1)}{2}\right)$

Where:

nn = Number of Nodes in N: nn = card(N)
nsn = Number of Survivable Nodes in N
nk = Number of Commodities in K: nk = card(K)
nl = Number of Facilities in L: nl = card(L)

Figure 2-9 – Problem size calculations

Parameters			Others	Obj	Number of constraints					Number of variables			
nn	nsn	nl	nk	29	30	31	32	33	Total	34	35	36	Total
5	-	2	20	1	100	9	5	10	124	10	20	400	430
10	3	2	90	1	5,544	287	67	45	5,943	45	90	56,700	56,835
17	4	2	272	1	47,720	[illegible]	[illegible]	136	[illegible]	136	272	[illegible]	[illegible]
17	-	2	272	1	[illegible]	[illegible]	17	136	[illegible]	136	272	[illegible]	[illegible]
17	17	2	272	1	[illegible]	[illegible]	[illegible]	136	[illegible]	136	272	[illegible]	[illegible]
30	6	2	870	1	558,888	9,395	654	435	569,372	435	870	16,651,800	16,653,105
50	10	2	2,450	1	6,787,480	68,109	2,790	1,225	6,859,604	1,225	2,450	336,140,000	336,143,675
50	-	2	2,450	1	122,500	1,224	50	1,225	124,999	1,225	2,450	6,002,500	6,006,175
100	--	2	9,900	1	990,000	4,949	100	4,950	999,999	4,950	9,900	98,010,000	98,024,850

Table 2-2 — Problem size calculations

Chapter 3

Model implementation

Previous chapters analysed the important components of the model and developed a corresponding mathematical formulation. Chapter 3 addresses the automation of the design processes, of which the model is the core component, to generate results and associated reports efficiently. Section 3.1. provides an overview of the Network Design Optimisation Tool (NDOT) specifically developed to support the implementation of this model. Section 3.2. describes how the NDHQ MAN data was collected and manipulated to be usable by the model through NDOT.

3.1. NDOT

To support the implementation and computational validation of the model developed in Chapter 2, NDOT, a 32-bit GUI-based application, was developed in parallel with the model. Essentially, NDOT is a telecommunication network design tool with manual and automated capabilities. A key component of NDOT is its interface with the Cplex optimisation solver which was used extensively to solve the problem studied. The intent of this section is to provide an overview of the key features of NDOT and a description of the Cplex-NDOT integration. Appendix B contains a more extensive description of the tool.

3.1.1. Overview

Essentially, NDOT provides a Graphical User Interface (GUI) that naturally supports network design functions. Figure 3-1 provides an example of the NDOT GUI. As expected from such GUI, the icon representation of network nodes can be dragged on the screen, the nodes and links can be double-clicked to view or edit their respective properties and, through speed buttons or pull-down menus, the user can add nodes and links as required.

More advanced features include the Random Network Generator (RNG) and the design optimisation algorithms. The RNG is mainly intended as a validation and debugging tool when developing design optimisation algorithms. It allows the user to generate a complete network (including a set of nodes and links, a traffic matrix, link costs, etc.) with some of those components being generated randomly. Additional important features include reporting, importing, exporting, printing and help capabilities. For more details on all these features, see Appendix B.

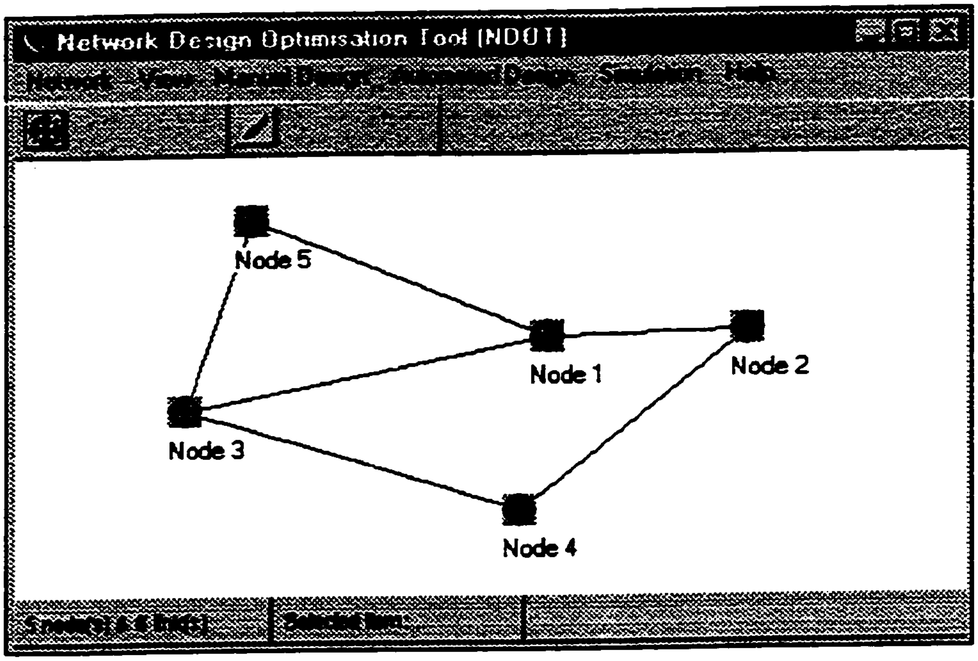


Figure 3-1 – NDOT graphical user interface

3.1.2. Cplex integration

The engine behind the advanced design optimisation capability of NDOT is Cplex 6.0, an MS-DOS-based linear optimisation solver. When solving a problem, NDOT will first take an input file, which includes node capacities and a traffic matrix as well as a second file containing the link costs. Through a set of forms, the user will then set all required problem parameters. All this information will then be recorded as the data of a MIP formulation to be read by Cplex. Cplex will then solve the MIP problem and generate a solution file. This solution file is then read by NDOT and converted to a more meaningful report and network graph. Figure 3-2 illustrates the interactions between NDOT and Cplex.

3.2. Data collection and initial parameter settings

This section explains how the necessary problem parameters were obtained and laid out according to the format required by the model developed in Chapter 2. Essentially, the network-specific data is either automatically generated through the RNG or loaded from an existing network file. On the other hand, the optimisation-specific data is entered through a set of entry screens. The most logical way to describe this data collection effort is to go through each of the steps in the sequence adopted by any user of NDOT. See Table 2-1 for a complete list of those parameters.

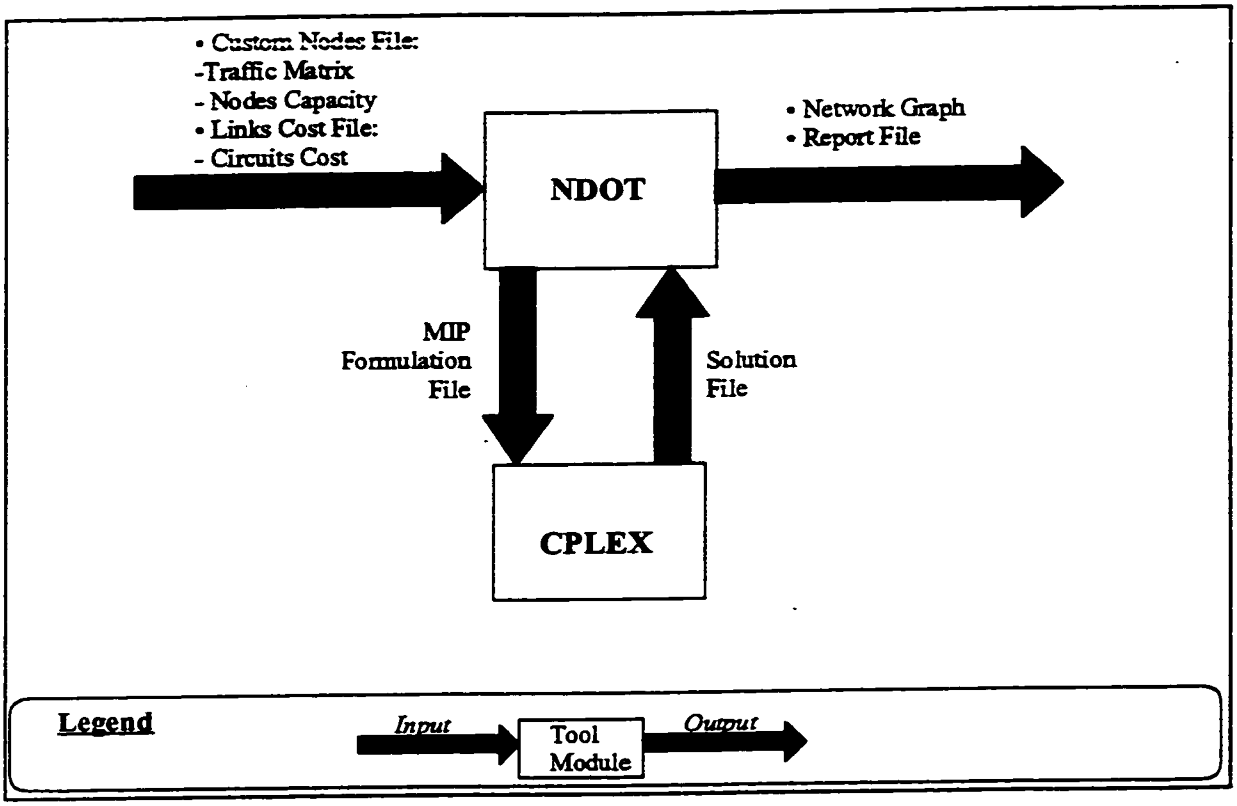


Figure 3-2: NDOT-Cplex interaction

3.2.1. Objective function

The first set of parameters required is related to the objective function defined by Equation (30) in Figure 2-8 and illustrated in Figure 3-3.

Facility costs (sc^1 & mrc_{ij}^1). As mentioned in Section 2.3.3., there are two components to the total cost of a given transmission facility, a one-time installation charge, referred to as service charges (sc), and monthly recurring charges (mrc). These charges will vary based on the type of facility and the distance between the end-points. Since the value of the parameter mrc_{ij}^1 depends on the distance between the end-points, a price quote for all 136 possible links (i.e. (17x16)/2)

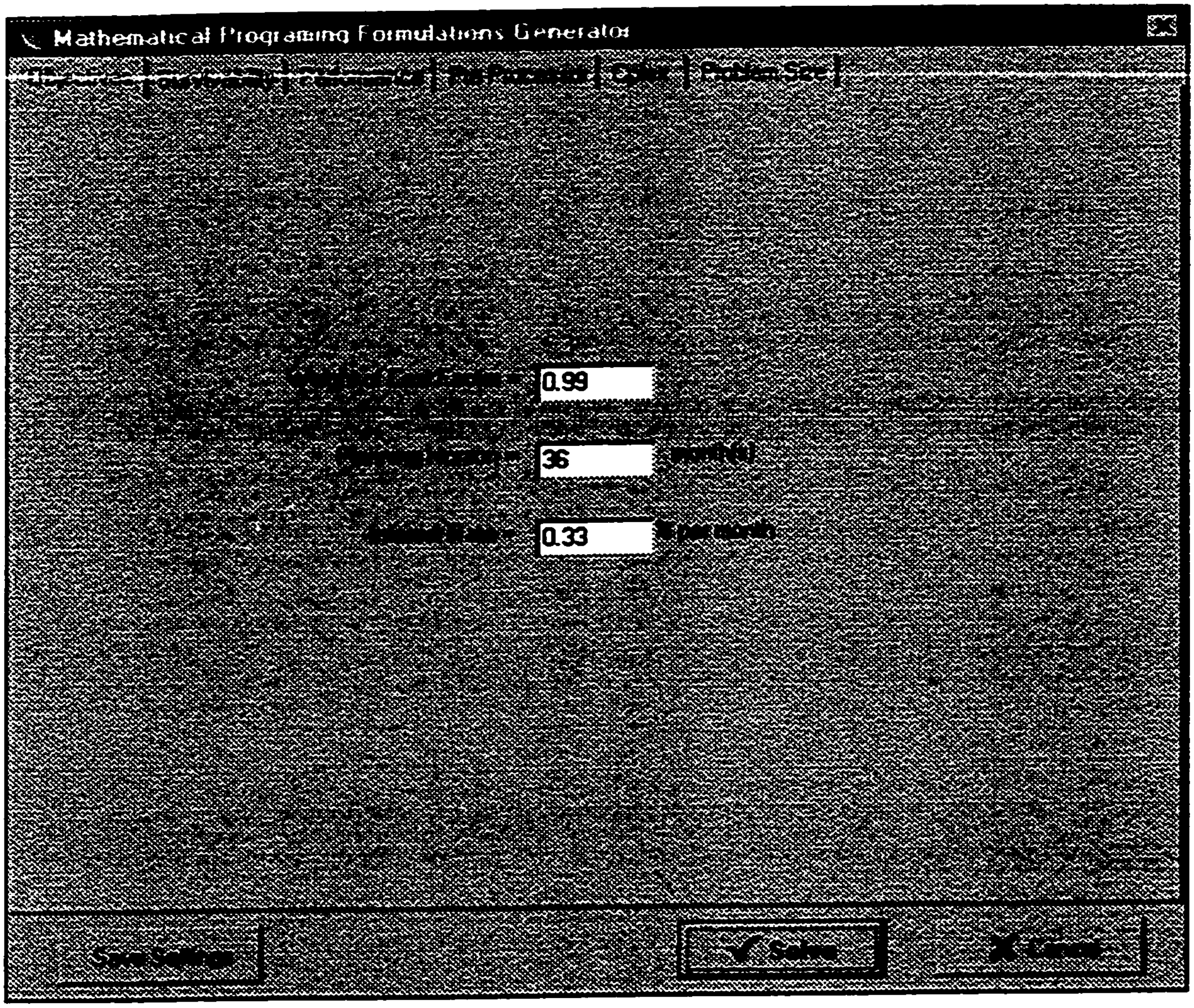


Figure 3-3: Objective function settings

and for all types of facilities had to be requested to get exact costs matrices (one per facility type). This requirement creates a significant amount of work for several network support staff and was therefore not done at this time. For the purpose of this thesis, distance-independent costs from one TSP have been used. The MRC used for each facility was obtained by averaging the current MRCs of the MAN circuits. Table 3-1 summarises the averaged (distance-independent) costs structure for the two types of facilities considered in the NDHQ MAN problem. As mentioned in

Facility Type	Capacity (bps)	SC ($)	MRC ($/month)
DSA	56,000	800	245
DS1	1,544,000	1,600	1,115

Table 3-1: Facilities costs structure

Section 1.4.3., this cost structure offers strong economies of scale. In fact, the breakeven point using ph=36 and ir=0.33% (as shown in Figure 3-3) is approximately 4.3. This means that any link with a requirement for a total capacity of 5 DSA or more will receive a T1.

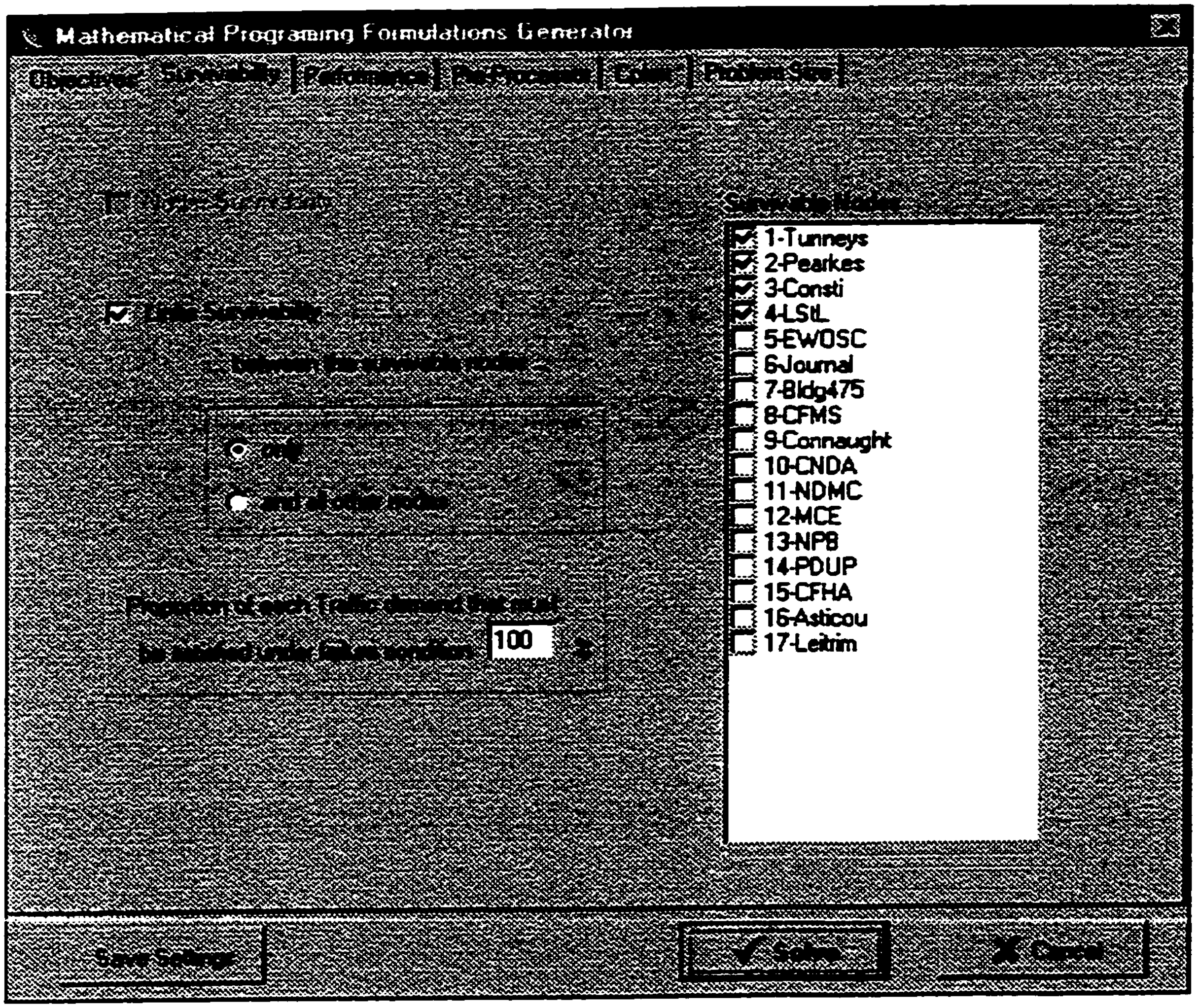
Multi-objective factor (α). Essentially, this parameter is a weight factor, which allows the user to balance the relative importance of each component of the objective function. For instance with $\alpha=1$, only the total cost is minimised and with $\alpha=0$, the total expected amount of flow on the network is minimised. The result of setting $\alpha=0$ is a graphical representation of the traffic matrix, since every OD-pair will be directly connected to minimise the total amount of traffic transmitted on the network. The appropriate value for α should be slightly smaller than 1. This ensures that the minimal cost solution is obtained, yet it will keep the commodities paths as short as possible within this minimum cost solution, thus ensuring that the total amount of traffic on the network is minimised. Hence, the parameter α must be set such that cost is the main objective criterion. The secondary criterion calls for the traffic to be routed as directly as possible, instead of randomly, as an outcome of a routing protocol such as OSPF. The actual value of α will therefore depend on the size (in bps) of the traffic demands and will be appropriately determined in Chapter 4 through experimentation.

Interest rate (ir). To calculate the NPV of a recurring constant cost, an interest rate is required. For the purpose of this thesis, an annual interest rate of 4% was used. In the case of the NDHQ MAN problem, a monthly rate of 0.33% was chosen to reflect the periodic nature of the payments.

Planning horizon (ph). A planning horizon of 36 months (3 years) was selected for the purpose of this problem. This value leaves sufficient time for the one-time charges to be absorbed and it is not too long so that new contracts can be negotiated to take advantage of newer technologies and/or cost reductions of leased facilities.

3.2.2. Survivability requirements

The next set of data and parameters required is shown in Figure 3-4, under the survivability screen.



☐ Node Survivability

☑ Link Survivability

between the survivable nodes

● only

○ and all other nodes

Proportion of each Traffic demand that must be satisfied under failure condition: 100 %

Survivable Nodes

☑ 1-Tunneys
☑ 2-Pearkes
☑ 3-Consti
☑ 4-LStL
☐ 5-EWOSC
☐ 6-Journal
☐ 7-Bldg475
☐ 8-CFMS
☐ 9-Connaught
☐ 10-CNDA
☐ 11-NDMC
☐ 12-MCE
☐ 13-NPB
☐ 14-PDUP
☐ 15-CFHA
☐ 16-Asticou
☐ 17-Leitrim

Figure 3-4: Survivability settings

Survivable nodes. The Service Level Commitment (SLC) [76 CG, 1998] identifies the four core buildings (Pearkes, Constitution, Louis St-Laurent and Tunney's Pasture) as high availability sites and requires link and node redundancy. Nodes redundancy is achieved inside each building by having two routers, while link redundancy is considered as part of this problem. For the purpose of this problem, survivability strictly between the four core buildings was required. It was therefore not required to achieve survivability between the four core buildings through other nodes (see Figures B-13 and B-14 for an illustration of the difference between the two scenarios).

Traffic matrix (dem_k). The traffic matrix used to solve the NDHQ MAN problem was derived through a six-step process (see Figure 3-5). Because of the unavailability of some of the

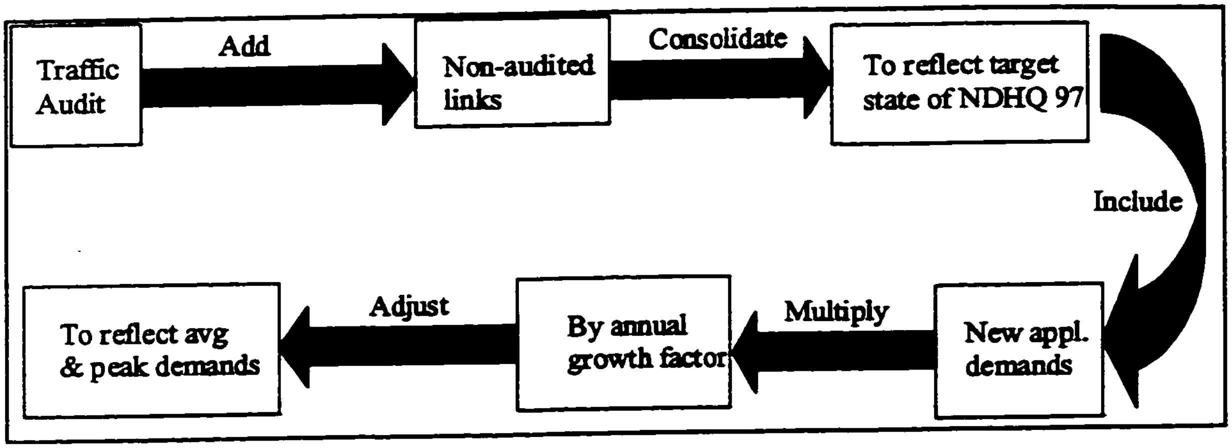


Figure 3-5: Traffic matrix generation processes

data, not all steps could be performed, which reduced significantly the accuracy of the traffic matrix obtained. The traffic flow analysis, reported by Ma *et al* [1998], forms the basis of the traffic matrix. The analysis was conducted using protocol analysers, which consider all the traffic transmitted on a given router interface and record the origin-destination pair and quantity of traffic observed over a pre-set amount of time. The throughput obtained is therefore an average value derived from the amount of bytes sent over the time interval of the analysis. The second step attempts to compensate for the fact that only selected links were analysed, by adding a minimum of traffic between the nodes not analysed, but already connected according to Figure 1-2. The third step consists of consolidating the traffic matrix to reflect the target state of the NDHQ consolidation project described in Section 1.3.1. For instance, if all users from a given building are to be transferred to another building, then the traffic demands associated with the vacated building will be added to the receiving building's traffic demands. In the fourth step, the expected traffic demands, for each new major application coming online (see Section 1.3.3.), are added to the traffic matrix. In Step five, the matrix is multiplied by a growth factor of 225% to reflect the annual traffic demand growth of approximately 150% [76 CG, 1998]. Finally, in Step six, a conversion factor is applied to reflect the fact that measures used up to this point are average demands and designing a network based on averages will definitely provide poor performance because of the bursty nature of data traffic. Using empirical data from the current NDHQ MAN, link utilisation analysis reveals that the peak-to-average utilisation ratio is approximately 400%. Using such a factor ensures that peaks of 100% utilisation will be minimised throughout the network.

Table 3-3 summarises the resulting traffic matrix used to solve the NDHQ MAN problem. For the following two main reasons, the accuracy of the traffic matrix obtained is low:

- Only 13 of the 40 links found in Figure 1-2 were included in the traffic flow analysis reported by Ma *et al* [1998], which leaves out a significant amount of traffic and certainly a large amount of unknown commodities, such as EWOSC-Pearkes, which would have been captured by analysing that particular link. That is why the second step of Figure 3-5 is required to attempt to correct this deficiency.
- One of the motivations for solving the NDHQ MAN problem is the impact of the large applications coming on-line over the next few years. At this time, the applications analysis is still under development and the results were not yet available for inclusion in the traffic matrix.

Nevertheless, for the purpose of this thesis, the traffic matrix obtained is sufficiently accurate to allow theoretical analysis of the results obtained. A more accurate traffic matrix would therefore be required to support a practical analysis to be conducted on the results obtained.

Reservation factor (δ_k^s). The proportion of the traffic demands that must be satisfied under failure conditions is 100% for all commodities. The impact of this parameter on the solution will be assessed and the associated results presented in Chapter 4.

3.2.3. Performance requirements

The next set of data and parameters required is shown in Figure 3-6, under the performance requirement screen.

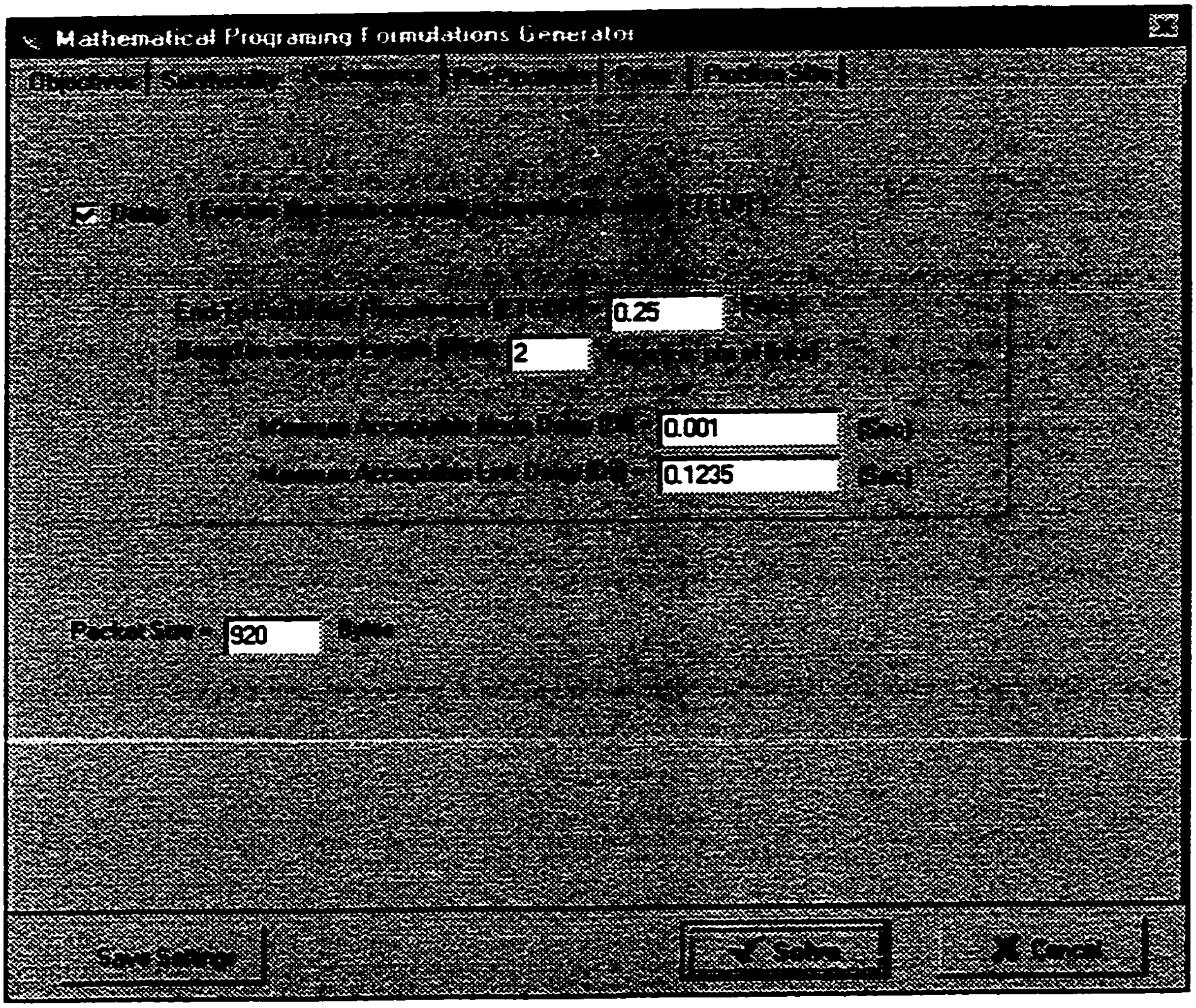
Node capacity (nc_i). The MAN is essentially composed of routers acquired from CISCO Inc. Table 3-3 summarises the processing capacities (in packet per seconds) for the two main router types used. These values were taken from the product documentation.

Packet size (ps). The SLC [76 CG, 1998] assumes 300 byte requests followed by 1500 byte (largest possible Ethernet frame) responses. Therefore, an average frame size of 900 bytes was

From\To	1- Tunneys	2- Pearkes	3- Constitution	4- LStL	5- EWOSC	6- Journal	7- Bldg475	8- CFMS	9- Connaugth	10- CNDA	11- NDMC	12- MCE	13- NPB	14- PDUP	15- CFHA	16- Asticou	17- Leitrim	Total OUT
1- Tunneys		414	417.6	355.5							0.9					146.7		1334.7
2- Pearkes	4482		2300.4	1112.4	146.7	0.9	147.6				97.2	146.7				147.6		8581.5
3- Constitution	320.4	1242		57.6		146.7	41.4				85.5				146.7	0.9	153.9	2195.1
4- LStL	325.8	2658.6	48.6				14.4						146.7	146.7		435.6		3776.4
5- EWOSC		146.7																146.7
6- Journal		28.8	146.7															175.5
7- Bldg475		176.4	0.9	18.9				146.7	146.7	146.7								636.3
8- CFMS							146.7											146.7
9- Connaugth							146.7											146.7
10- CNDA							146.7											146.7
11- NDMC	0.9	6.3	2023.2															2030.4
12- MCE		146.7																146.7
13- NPB				146.7														146.7
14- PDUP				146.7														146.7
15- CFHA			146.7															146.7
16- Asticou	146.7	348.3	227.7	153														875.7
17- Leitrim			147.6															147.6
Total IN	5275.8	5167.8	5459.4	1990.8	146.7	147.6	643.5	146.7	146.7	146.7	183.6	146.7	146.7	146.7	146.7	730.8	153.9	20926.8

Table 3-2: Final traffic matrix (kbps)

used initially, which translates into an average packet size of 920 bytes, when adding the IP overhead.



☑ [illegible]

[illegible] 0.25 [illegible]

[illegible] 2 [illegible]

[illegible] 0.001 (Sec)

[illegible] 0.1235 (Sec)

Packet Size = 920 Bytes

Figure 3-6: Performance settings

Router Type	Capacity (pps)
CISCO 2500 Series	50,000
CISCO 7000 Series	100,000 +

Table 3-3: Nodes capacity

ETEDR, nd_i, ad_{ij} & R. The SLC [76 CG, 1998] for the MAN states that the desirable maximum round-trip delay must not exceed 1 second or 0.5 seconds one-way. This delay limitation for example is between a user's terminal and a server. Therefore, on the inter-building backbone only, a one-way ETEDR of 0.25 seconds will be used, which leaves approximately 125ms at each end to cross the local building infrastructure. This is a fair estimation since Local Area Networks within buildings have a much greater capacity of at least 10 Mbps. When looking at Figure 1-2 and considering the concept of the four-core building with satellite buildings connected to them, it is expected that most commodities will reach their destination using three links or less. Therefore, the parameter R was initially set to 3.

Based on the ETEDR and R, we can now set the node and arc delay values according to Equation (26). The user can test a particular value of nd_i or ad_{ij} and the corresponding value for the other delay will be automatically calculated. Several values were analysed and results presented in Chapter 4.

3.2.4. Pre-processor settings

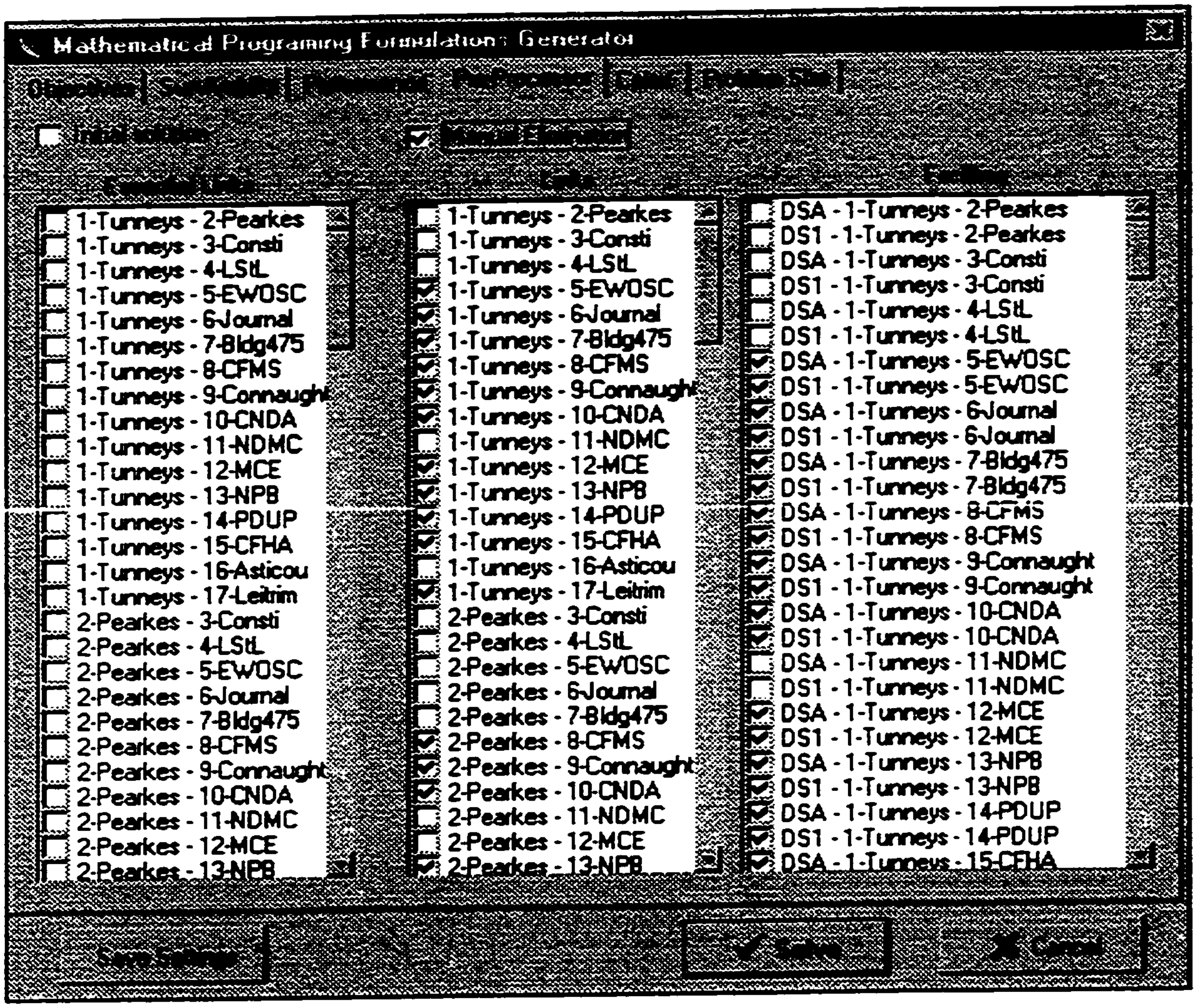
The next set of data and parameters required is shown in Figure 3-7, under the pre-processor settings screen. Essentially, this screen allows the user to influence the optimal solution by forcing the existence of certain links and/or reduce the size of the problem by eliminating links and facilities deemed not required.

To reduce the size and complexity of the NDHQ MAN problem without sacrificing optimality, a careful elimination of links and facilities was done before the optimisation process. In fact, through a careful examination of the traffic matrix, several topology design variables x_{ij}, can be eliminated. For instance, if a given node exchanges traffic with only one other node, then the optimal solution will definitively connect these two nodes directly, as it will minimise end-to-end delay for the corresponding commodities and potentially reduce the solution cost.

Furthermore, not all facilities are valid candidates on every link, which allows the additional elimination of several arcs sizing variables y_{ij}^{l}. Keeping in mind the two nodes from the previous paragraph, if the total traffic demand of the corresponding commodities does not exceed 20 Kbps, for instance, then a DS1 facility would never be installed on that link and can therefore be eliminated from the list of candidates for that link.

These two types of elimination can substantially reduce the solution complexity of the problem, since they directly affect the number of binary (x_{ij}) and general integer (y_{ij}^{l}) variables.

As a direct consequence, all flow variables f(s,ij,k) associated with the eliminated links are also eliminated. With a traffic matrix density of 20% (see Table 3-2), applying the pre-processor to the NDHQ MAN problem is very effective as it can reduce the number of variables by as much as 50%.



☑ [illegible]

☐ 1-Tunneys - 2-Pearkes
☐ 1-Tunneys - 3-Consti
☐ 1-Tunneys - 4-LStL
☐ 1-Tunneys - 5-EWOSC
☐ 1-Tunneys - 6-Journal
☐ 1-Tunneys - 7-Bldg475
☐ 1-Tunneys - 8-CFMS
☐ 1-Tunneys - 9-Connaught
☐ 1-Tunneys - 10-CNDA
☐ 1-Tunneys - 11-NDMC
☐ 1-Tunneys - 12-MCE
☐ 1-Tunneys - 13-NPB
☐ 1-Tunneys - 14-PDUP
☐ 1-Tunneys - 15-CFHA
☐ 1-Tunneys - 16-Asticou
☐ 1-Tunneys - 17-Leitrim
☐ 2-Pearkes - 3-Consti
☐ 2-Pearkes - 4-LStL
☐ 2-Pearkes - 5-EWOSC
☐ 2-Pearkes - 6-Journal
☐ 2-Pearkes - 7-Bldg475
☐ 2-Pearkes - 8-CFMS
☐ 2-Pearkes - 9-Connaught
☐ 2-Pearkes - 10-CNDA
☐ 2-Pearkes - 11-NDMC
☐ 2-Pearkes - 12-MCE
☐ 2-Pearkes - 13-NPB

☐ 1-Tunneys - 2-Pearkes
☐ 1-Tunneys - 3-Consti
☐ 1-Tunneys - 4-LStL
☑ 1-Tunneys - 5-EWOSC
☑ 1-Tunneys - 6-Journal
☑ 1-Tunneys - 7-Bldg475
☑ 1-Tunneys - 8-CFMS
☑ 1-Tunneys - 9-Connaught
☑ 1-Tunneys - 10-CNDA
☐ 1-Tunneys - 11-NDMC
☑ 1-Tunneys - 12-MCE
☑ 1-Tunneys - 13-NPB
☑ 1-Tunneys - 14-PDUP
☑ 1-Tunneys - 15-CFHA
☐ 1-Tunneys - 16-Asticou
☑ 1-Tunneys - 17-Leitrim
☐ 2-Pearkes - 3-Consti
☐ 2-Pearkes - 4-LStL
☐ 2-Pearkes - 5-EWOSC
☐ 2-Pearkes - 6-Journal
☐ 2-Pearkes - 7-Bldg475
☑ 2-Pearkes - 8-CFMS
☑ 2-Pearkes - 9-Connaught
☑ 2-Pearkes - 10-CNDA
☐ 2-Pearkes - 11-NDMC
☐ 2-Pearkes - 12-MCE
☑ 2-Pearkes - 13-NPB

☐ DSA - 1-Tunneys - 2-Pearkes
☐ DS1 - 1-Tunneys - 2-Pearkes
☐ DSA - 1-Tunneys - 3-Consti
☐ DS1 - 1-Tunneys - 3-Consti
☐ DSA - 1-Tunneys - 4-LStL
☐ DS1 - 1-Tunneys - 4-LStL
☑ DSA - 1-Tunneys - 5-EWOSC
☑ DS1 - 1-Tunneys - 5-EWOSC
☑ DSA - 1-Tunneys - 6-Journal
☑ DS1 - 1-Tunneys - 6-Journal
☑ DSA - 1-Tunneys - 7-Bldg475
☑ DS1 - 1-Tunneys - 7-Bldg475
☑ DSA - 1-Tunneys - 8-CFMS
☑ DS1 - 1-Tunneys - 8-CFMS
☑ DSA - 1-Tunneys - 9-Connaught
☑ DS1 - 1-Tunneys - 9-Connaught
☑ DSA - 1-Tunneys - 10-CNDA
☑ DS1 - 1-Tunneys - 10-CNDA
☐ DSA - 1-Tunneys - 11-NDMC
☐ DS1 - 1-Tunneys - 11-NDMC
☑ DSA - 1-Tunneys - 12-MCE
☑ DS1 - 1-Tunneys - 12-MCE
☑ DSA - 1-Tunneys - 13-NPB
☑ DS1 - 1-Tunneys - 13-NPB
☑ DSA - 1-Tunneys - 14-PDUP
☑ DS1 - 1-Tunneys - 14-PDUP
☑ DSA - 1-Tunneys - 15-CFHA

Figure 3-7: Pre-processor settings

3.2.5. Cplex settings

One of the key advantages of Cplex is the large number of parameters that can be adjusted to obtain the best solution strategy for a particular type of problem. The effect of these adjustments can be significant on the amount of time and/or memory required to solve a given problem. Before solving the NDHQ MAN problem, a small 5-node problem was generated with a similar structure. This test problem was then solved with different combinations of parameters to determine the best combination of Cplex parameters value. These settings were then used for the NDHQ MAN problem. Table 3-4 summarises these results and Appendix D provides a description of the different parameters analysed (top section of Table 3-4). Essentially, the bottom section includes the performance measures used to make the decisions. Column A represents a baseline from which the comparisons where made. In the remaining columns, the parameters values in bold highlight the differences with respect to that baseline (Column A).

Varying the "mipgap" tolerance to a very precise degree has shown that the optimal value of the objective function is 8180.067. Since designers do not need a real-time solution, they are willing to tolerate a longer solution time to get the optimal solution. Column M summarises the combination of parameters expected to generate the optimal solution. Finally, all the results presented in this subsection and Chapter 4 have been generated with NDOT installed on an IBM-compatible PC with a 200 MHz Pentium Processor and 48 MB of RAM.

	A	B	C	D	E	F	G	H	I	J	K	L	M	N	O	P	Q
set preprocessing presolve	y	y	y	y	y	y	y	y	y	y	y	y	y	y	n	y	y
set preprocessing coeffreduce	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	0	2
set preprocessing relax	y	y	y	y	y	y	y	y	y	y	y	y	y	n	y	y	y
Set mip strategy rootheuristic	0	0	0	0	0	0	0	0	0	0	-1	-1	-1	-1	-1	-1	-1
set mip strategy nodeselect	2	3	3	3	3	3	3	3	3	3	3	3	2	2	2	2	2
set mip strategy variableselect	1	1	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3
set mip strategy branch	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0
set mip tolerances mipgap	0.01	0.01	0.01	0.01	0.1	0.0001	0.01	0.01	0.01	0.01	0.01	0.05	0.01	0.01	0.01	0.01	0.01
set mip strategy startalgorithm	2	2	2	2	2	2	3	3	3	1	2	2	2	2	2	2	2
set mip strategy subalgorithm	2	2	2	2	2	2	3	3	3	1	2	2	2	2	2	2	2
set simplex dgradient	2	2	2	2	2	2	n/u	n/u	n/u	n/u	2	2	2	2	2	2	2
set simplex pgradient	n/u	n/u	n/u	n/u	n/u	n/u	n/u	n/u	n/u	2	n/u	n/u	n/u	n/u	n/u	n/u	n/u
set simplex netfind	n/u	n/u	n/u	n/u	n/u	n/u	1	2	3	n/u	n/u	n/u	n/u	n/u	n/u	n/u	n/u
Solution Time	300.8	300.17	240	262	137	232.34	300.36	300.24	300.23	300.33	230	172.22	210	220.83	216	224	214
Best Integer Soln Obtained	8291.53	8441.168	8180.067	8180.067	8235.391	8180.067	8199.492	8199.492	8180.067	8180.067	8180.067	8199.492	8180.067	8180.067	8180.067	8180.067	8180.067
Is it Optimal?	n	n	y	y	y	y	n	n	n	n	y	y	y	y	y	y	y
Nbr Nodes Solved	29424	25817	2284	2675	1251	2383	1681	1672	1754	2064	2284	1646	2225	2225	2225	2225	2225
Nbr Nodes Remaining	3243	12425	62	52	242	0	124	127	71	209	62	183	0	0	0	0	0
Solution Cost	5703	5380	4970	4970	4970	4970	4970	4970	4970	4970	4970	4970	4970	4970	4970	4970	4970
Nbr Links	13	12	9	9	10	9	9	9	9	9	9	9	9	9	9	9	9
Total Amount of Flow	2593234	3066548	3216037	3216037	3270361	3216037	3234462	3234462	3216037	3216037	3216037	3234462	3216037	3216037	3216037	3216037	3216037

Table 3-4: Cplex parameters analysis

Chapter 4

Experimental results

The intent of this chapter is to present the results obtained when solving the NDHQ MAN problem introduced earlier. Because of the limited data available to develop an accurate traffic matrix of the problem and unexpected growth of the network to more than 17 nodes by 1999, these results cannot be directly implemented. Nevertheless, they are indicative of a response to a policy formed in 1997 bringing much more insight than results obtained from a pure randomly generated network.

Section 4.1. reiterates the important assumptions made throughout this thesis to obtain the final model described in Chapter 2 and the necessary data from the NDHQ MAN problem. This section becomes an important reference when analysing the results obtained. In Section 4.2., a first set of results, necessary to set additional parameters, are presented. These results provide the optimal combination of parameters values to solve the NDHQ MAN problem. In Section 4.3., the final solution is presented along with a sensitivity analysis on key parameters and an overall validation of the results obtained.

4.1. Summary of assumptions

The assumptions made to support the validation of the model are summarised in the following subsections.

4.1.1. Objective function

Leased facility costs. For the purpose of this problem, a distance-independent set of values mrc has been used for each type of facilities, using the fees incurred with the current network links. The reason for this simplification is that recording values of sc and mrc for all types of facilities, for all possible links and from all service providers in the Ottawa-Hull Metropolitan area requires a significant amount of work from several network support personnel, which was deemed unnecessary at this time. Nevertheless, when actual decisions are made based on the results obtained, then such resource-intensive exercise is required and justifiable to ensure accuracy of the data provided to the model.

OSPF model. The OSPF routing algorithm was approximated by minimising the total amount of traffic throughout the network instead of using Equation (27), a non-linear equation. Until formal validation of the model can be performed (e.g. through simulation), it is deemed unnecessary to implement the very accurate and non-linear model for the OSPF routing protocol.

4.1.2. Survivability requirements

Survivability requirement. Experts consider the probability of a second network failure occurring, before the first can be repaired, to be negligible [Lloyd *et al*, 1995], which is in agreement with the network failure statistics received for the NDHQ MAN. Thus, a node-disjoint 2-connected topology will satisfy survivability requirements of most problems. The reader is referred to Appendix A for additional explanations on node-disjoint 2-connected networks.

Traffic matrix. As mentioned in Section 3.2.2., the traffic matrix obtained is far from accurate. First, the traffic analysis [Ma *et al*, 1998] did not include all the network nodes, which resulted in missing commodities. Also, because the applications analysis has not been completed yet by the MAN support personnel, its impact on the overall capacity requirement of the MAN could not be evaluated at this time.

4.1.3. Performance requirements

ETED model. In Section 2.3.3.4., a linear model governing the relationship between the ETEDR, ad_{ij}, nd_i and R was selected instead of a potentially more accurate non-linear model, which considers each commodity individually. Essentially, this abstraction was done to maintain a linear model and because its impact on the model accuracy was deemed minimal.

Loads on the routers. The load considered on the router only covers the inter-building loads (i.e. from the traffic matrix). In practice, these routers are used for internal traffic as well, to isolate traffic on their respective IP networks. Furthermore, in the core buildings, there really are two routers for survivability purposes and only one was considered. As a result of these simplifications, the expected loads obtained in Section 4.3. represent the inter-building portion of the load placed on these routers.

Infinite node buffer capacity. As currently formulated, the performance model (based on the M/M/1 model) assumes infinite buffer size. In practice, routers have finite buffer capacity to store packets before and/or after processing. Such simplification turned out to be satisfactory when considering the light load expected on the nodes as mentioned in the previous paragraph and confirmed in Section 4.3.

4.2. Final parameters settings

As one will observe, some of the model parameters are user-driven (i.e. α, R, nd_i and ad_{ij}), while others are system-driven (ph, ir, ps, *etc.*). Essentially, user-driven parameters are those over which the user has complete control independently of the system requirements. On the other hand, system-driven parameters are defined by the system requirements (see Section 3.2.) and the user has limited control over their values. Therefore, before solving the NDHQ MAN problem, a highly constrained version of the problem was used to further refine the value of these user-driven parameters. Different values of these parameters were used and their respective influence on the solution was measured. The following subsections summarise these results and related conclusions.

4.2.1. Multi-objective factor (α)

The first parameter fixed was α, the objective function weight factor (see Equation 30). The approach taken was simply to start with the two extreme cases (i.e. α=0 and α=1) so as to set the boundaries. As expected and shown in Table 4-1, α=1 provides the minimum possible cost

Parameters Settings	* Alpha	1	0.9999	0.999	0.99	0.95	0.9	0
	ph	36	36	36	36	36	36	36
	ir	0.33%	0.33%	0.33%	0.33%	0.33%	0.33%	0.33%
	Links Surviv settings	0	0	0	0	0	0	0
	Gamma	n/a	n/a	n/a	n/a	n/a	n/a	n/a
	Delay setting	Y	Y	Y	Y	Y	Y	Y
	ps (Bytes)	920	920	920	920	920	920	920
	ETEDR (sec)	0.25	0.25	0.25	0.25	0.25	0.25	0.25
	* R	3	3	3	3	3	3	3
	* nd (sec)	0.0175	0.0175	0.0175	0.0175	0.0175	0.0175	0.0175
	* ad (sec)	0.06	0.06	0.06	0.06	0.06	0.06	0.06
	Preprocessor Eliminations	Tight	Tight	Tight	Tight	Tight	Tight	None
	mipgap	0.01	0.01	0.01	0.01	0.01	0.01	0.01
Cplex Results	Solution Time (sec)	5,582	3,613	4,528	2,191	313	177	28
	Best Integer Soln Obtained	1,012,027	1,014,221	1,033,970	1,231,485	2,080,514	3,133,705	20,926,800
	Is it Optimal?	Y	Y	Y	Y	Y	Y	Y
	Current MIP best bound	1,004,893	1,005,912	1,026,203	1,222,888	2,064,271	3,102,725	n/a
	Gap	7,134	8,309	7,767	9,388	16,242	30,980	n/a
	Nbr Iterations	191,042	138,480	16,028	86,840	9,169	5,360	210
	Nbr Nodes Solved	8,062	7,828	10,323	5,883	1,235	683	34
	Nbr Nodes Remaining	1	4	4	4	11	7	-
NDOT Results	Solution Cost	$1,012,034	$1,012,034	$1,012,034	1,012,034	1,024,114	1,063,503	1,378,615
	Nbr Links	19	19	19	19	19	19	27
	Total Amount of Flow	23,204,466	22,954,868	22,954,868	22,954,868	22,152,267	21,765,600	20,926,800

Table 4-1: Parameters analysis results (α)

solution, while $\alpha=0$ provides an expensive solution, since all commodities' Origin-Destination (OD)-Pairs are directly connected to ensure shortest possible paths. Several values of α were tested and among those, $\alpha=1$, 0.9999, 0.999 and 0.99 yield the minimum cost solutions. Of these four sets of results, the last three generate the shortest paths for all commodities and therefore provide the best numerical approximation of the by-criterion optimum. The fourth one ($\alpha=0.99$) requires the least time to solve and was therefore selected. This set of results served as the base for the next set of impact analysis, with an aim of further refining the solution as new user-defined parameters become fixed. Again, depending on the user's relative preference for the two objectives, a different value of α could be selected, as illustrated in Figure 4-1.

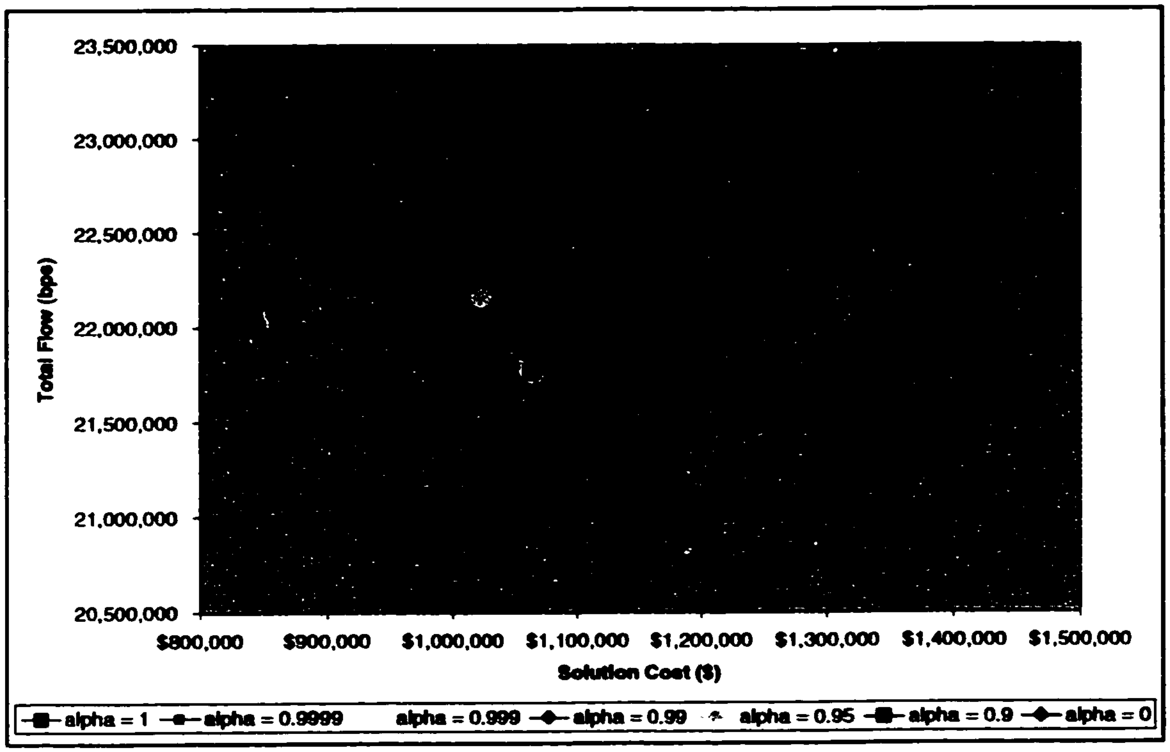


Figure 4-1: Total flow vs solution cost

4.2.2. R, nd_i and ad_{ij}

The second set of parameters fixed is related to Equation (26) of Chapter 2. In this case, the objective is to obtain the best combination of values for R, nd_i and ad_{ij}, given a certain ETEDR. The optimal solution will be obtained by adequately balancing these three values with the actual nodes and links utilisation. That is why some experimentation was required. Table 4-2 illustrates the results obtained with several combinations of values for R, nd_i and ad_{ij}. As mentioned in the previous subsection, the first column repeats the best results obtained in Table 4-1 for comparison purposes.

		Base	A	B	C	D	E	F	G
Parameters Settings	* Alpha	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
	pt	35	[illegible]	[illegible]	35	[illegible]	35	35	[illegible]
	L	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
	Links Surviv settings	0	[illegible]	[illegible]	0	[illegible]	0	0	[illegible]
	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
	Delay settings	Y	Y	Y	Y	Y	Y	Y	Y
	ps (Bytes)	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
	ETEDR (sec)	0.25	0.25	0.25	0.25	0.25	0.25	0.25	0.25
	* R	3	3	3	3	4	4	2	2
	* nd (sec)	0.0175	0.001	0.01	0.0001	0.01	0.001	0.01	0.001
	* ad (sec)	[illegible]	[illegible]	0.07	0.0532	0.05	0.06125	0.11	0.1225
	Preprocessor Eliminations	Tight	Tight	Tight	Tight	Tight	Tight	Tight	Tight
	mipgap	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01
Cplex Results	Solution Time (sec)	2,181	1,477	1,478	1,314	[illegible]	2,281	911	[illegible]
	Best Integer Soln Obtained	1,231,485	1,208,482	1,214,970	1,206,410	[illegible]	1,231,355	1,205,546	[illegible]
	Is it Optimal?	Y	Y	Y	Y	Y	Y	Y	Y
	Current MIP best bound	1,222,085	[illegible]	[illegible]	1,197,613	1,227,807	1,222,145	[illegible]	[illegible]
	Gap	9,380	9,704	6,351	8,797	7,826	9,211	11,883	8,321
	Nbr Iterations	[illegible]	45,381	[illegible]	[illegible]	61,726	[illegible]	34,429	[illegible]
	Nbr Nodes Solved	5,823	3,036	[illegible]	3,184	5,720	5,878	2,486	[illegible]
	Nbr Nodes Remaining	4	4	1	3	4	-	19	6
NDOT Results	Solution Cost	1,012,034	984,725	983,826	984,725	1,024,114	1,012,034	984,725	984,725
	Nbr Links	19	19	19	19	19	19	19	19
	Total Amount of Flow	22,954,868	23,159,224	23,108,772	23,154,048	22,176,800	22,944,852	23,067,836	[illegible]

Table 4-2: Parameters analysis results (R, nd_i and ad_{ij})

The first obvious observation is that the values initially selected (Base column) are definitely not optimal from an economical perspective. To improve the solution cost, a compromise in total flow and performance is required (i.e. reducing R to 2). Again, using the same argument that cost is the primary objective, columns A, C, F and G provide the least expensive solutions. Figure 4-2 is provided to compare the performance trade-offs between these four scenarios.

The intent was to proceed by elimination, starting with the best results (Column G). According to Figure 4-2 (looking at the results from Column G), there are only two commodities for which the expected ETED exceeds the ETEDR of 250 ms. A more in-depth analysis of the routing of these two commodities reveals that we are in fact dealing with multiple routes in both cases (see Table 4-3). In other words, both commodities are routed over multiple distinct paths. In practice, such behaviour is certainly possible in packet switched networks where reordering and re-assembly occurs at the destination node. In the case of the MAN, a packet-switched network operates on top of the TSP's circuit-switched network. In fact, the point-to-point facilities between the TSP's termination equipment in the NDHQ buildings are really logical connections, since they potentially go through a series of switching nodes. Therefore, with the

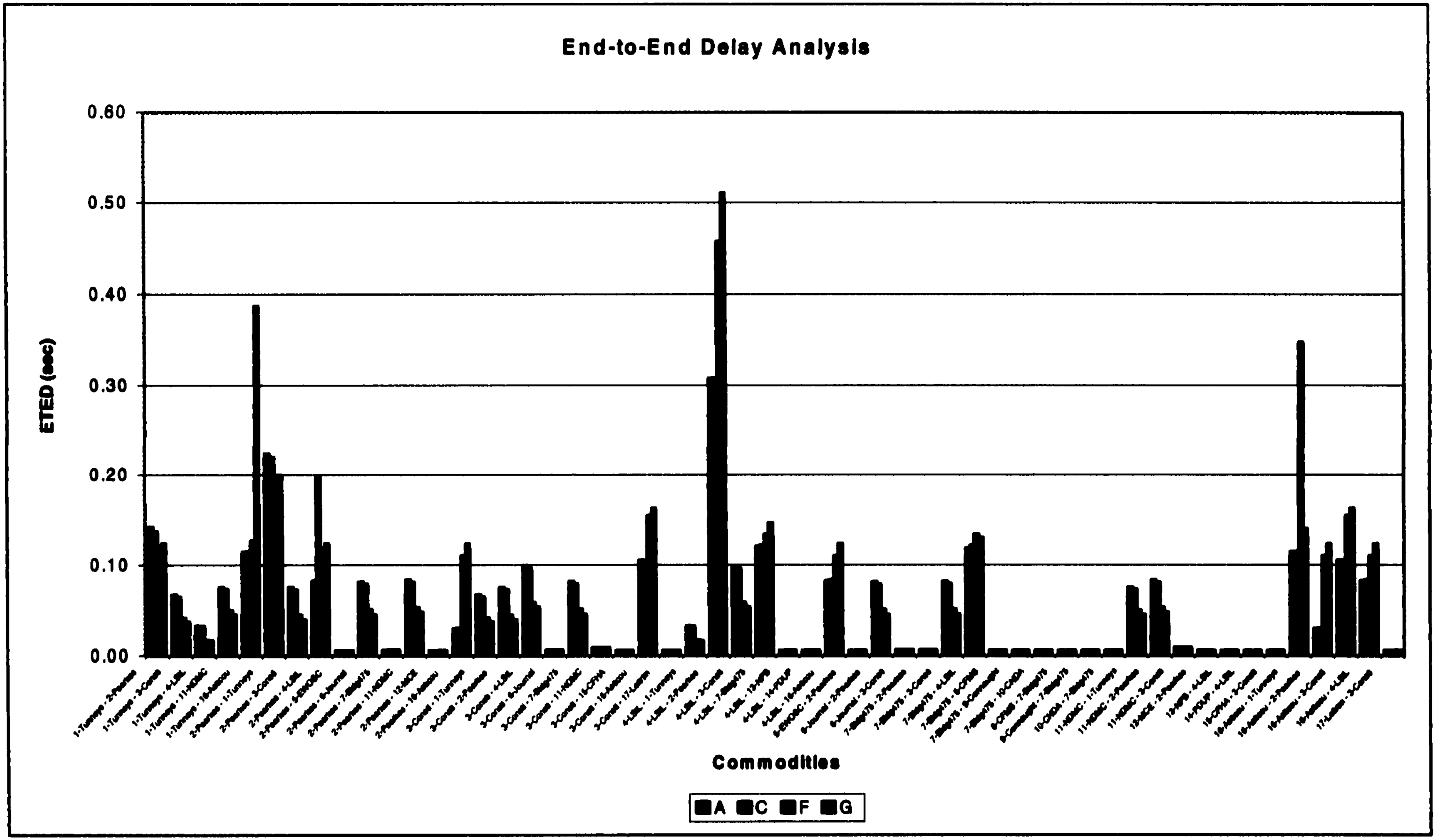


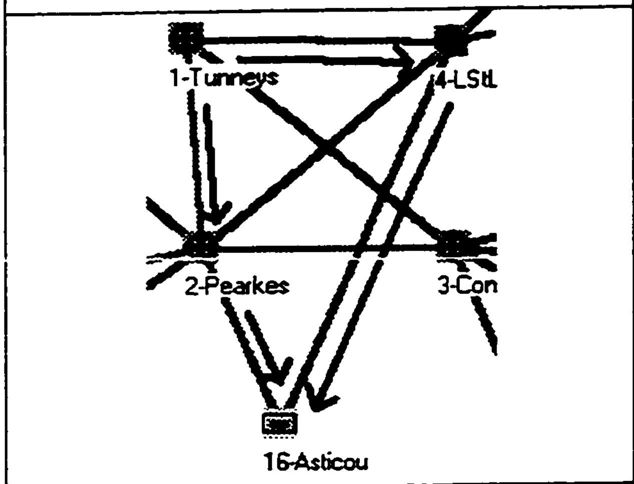
Figure 4-2: End-to-end delay analysis

Commodity: 1-Tunneys - 16-Asticou

Total traffic demand: 146,700 bps

Expected End to End Delay: 0.388 Sec

Direction	Link ID	Flow	Exp. Delay
>	1-Tunneys-2-Pearkes	78,750	0.124
>	1-Tunneys-4-LStL	67,950	0.016
>	2-Pearkes-16-Asticou	78,750	0.124
>	4-LStL-16-Asticou	67,950	0.124



Commodity: 4-LStL - 2-Pearkes

Total traffic demand: 2,658,600 bps

Expected End to End Delay: 0.511 Sec

Direction	Link ID	Flow	Exp. Delay
>	1-Tunneys-2-Pearkes	80,340	0.124
<	1-Tunneys-4-LStL	80,340	0.016
<	2-Pearkes-4-LStL	1,897,105	0.124
<	2-Pearkes-16-Asticou	68,1155	0.124
>	4-LStL-16-Asticou	68,1155	0.124

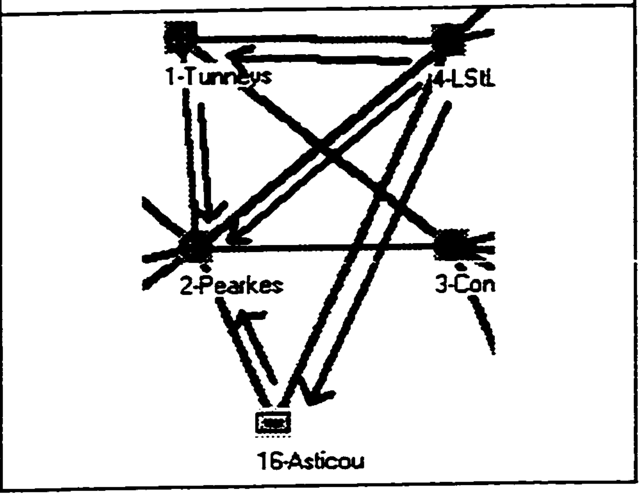


Table 4-3: Excessive delays analysis

MAN being a packet switched (datagram) network, it is expected that some commodities' packets will be routed over multiple paths and these packets will in fact be reordered and reassembled at the destination node. Having now established the fact that routing over multiple paths makes practical sense, the ETED measures obtained for the two commodities presented in Table 4-3 can be corrected to reflect the ETED of the worst path. The corrected ETED for both commodities becomes 0.248 sec, which satisfies the ETEDR for the network. This result certainly makes sense since the parameter R was set to 2 and these two commodities are using paths of at most 2 links. Therefore, the parameter settings of Column G in Table 4-2 will be used and carried onto the next analysis. The resulting topology is shown in Figure 4-3.

4.2.3. Survivability

Now that the important parameters are all adjusted, survivability requirements have to be taken into consideration. The analysis of failures between the 4 core buildings only requires that

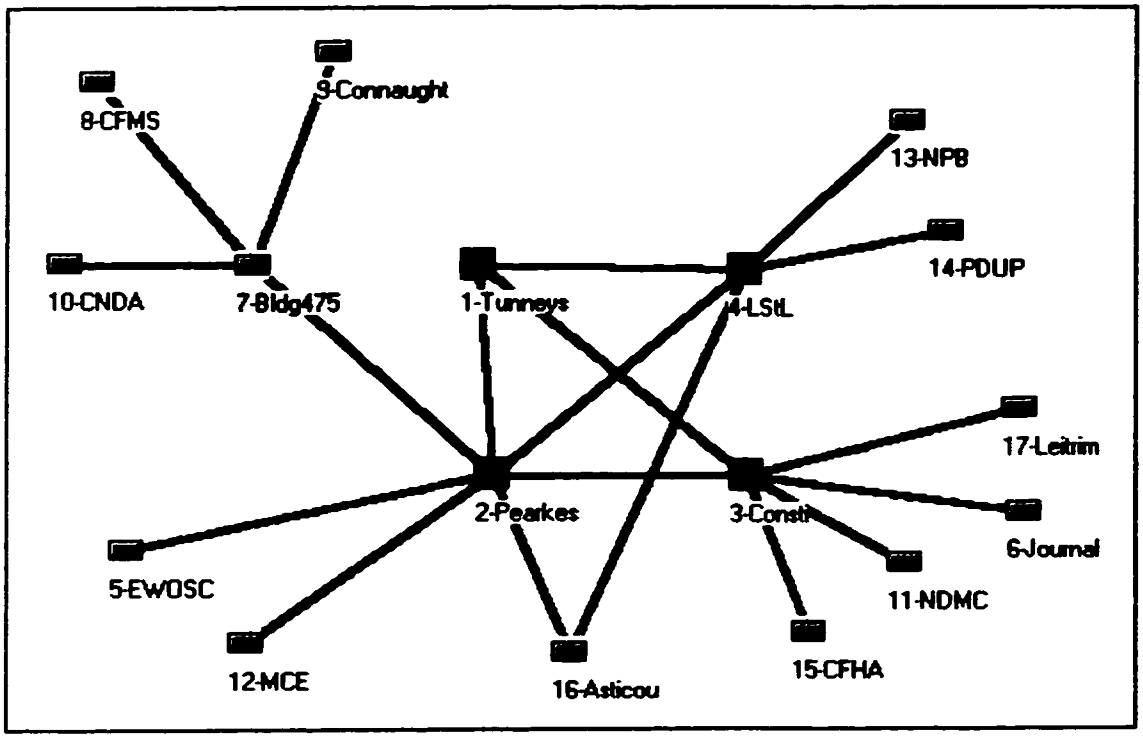


Figure 4-3: Baseline solution topology

Parameters Settings	* Alpha	0.99	0.99
	ph	36	36
	lr	0.33%	0.33%
	Links Surviv settings	0	0
	Gamma	n/a	n/a
	Delay setting	Y	Y
	ps (Bytes)	920	920
	ETEDR (sec)	0.25	0.25
	* R	2	2
	* nd (sec)	0.001	0.001
	* ad (sec)	0.1235	0.1235
	Preprocessor Eliminations	Tight	Tighter
	mipgap	0.01	0.01
Cplex Results	Solution Time (sec)	1,085	7
	Best Integer Soln Obtained	1,205,256	1,230,044
	Is it Optimal?	Y	Y
	Current MIP best bound	1,196,935	1,223,654
	Gap	8,321	6,389
	Nbr Iterations	39,158	464
	Nbr Nodes Solved	2,905	82
	Nbr Nodes Remaining	6	1
NDOOT Results	Solution Cost	984,725	1,012,034
	Nbr Links	19	18
	Total Amount of Flow	23,038,580	22,813,695

Table 4-4: Parameters analysis results (survivability)

the number of possible connections between any satellite and core building be restrained to one. The obvious disadvantage to this approach, as shown in Table 4-4, is an increased cost. On the other hand, these added constraints (through the pre-processor), simplify the topology of the final solution by enforcing a star topology around each core building. Furthermore, it ensures that satellite buildings will only be used to transfer their respective commodities during failure conditions. In fact, if we leave more than one possible connection out of a satellite building and only assess the impact of failures on inter-core building links, the cheapest solution totally by-passes the survivable links and the satellite buildings are used to transfer other commodities. The first column of Table 4-4 is essentially column G carried over from Table 4-2 for comparison purposes. The second column provides the settings and results associated with adding constraints to limit the number of possible connections from any satellite node to one. The reader will note a significant reduction in solution time and a 2.77% increase in the solution cost ($27,309 over three years). With this additional simplification, the problem becomes much easier to solve. The resulting topology is shown in Figure 4-4, which translates in eliminating the link between "Asticou" and "Pearkes" from Figure 4-3.

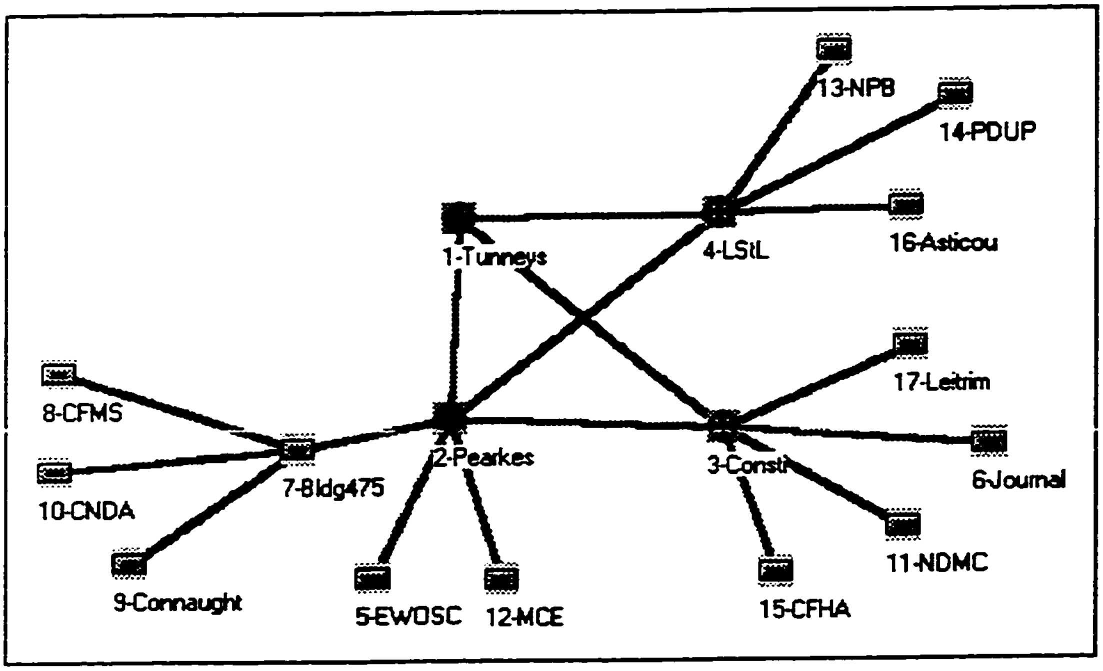


Figure 4-4: Tighter solution topology

4.3. Final solution

Having now set the scene for the consideration of the survivability requirement, the final solution can now be obtained. Essentially, when adding this requirement (with $\delta = 100\%$), a slightly different topology is obtained with one additional link between "Consti" and "LStL". For the purpose of this thesis, this solution, illustrated in Figure 4-5, is the recommended solution that will be further analysed. As will be shown later in this section, there is an important cost increase associated with $\delta = 100\%$. In practice, the decision to select a certain level of survivability for the MAN is very important. It would require sensitivity analysis results on δ (as shown in Subsection 4.3.2.) to allow the stakeholders to make the most cost-effective decision.

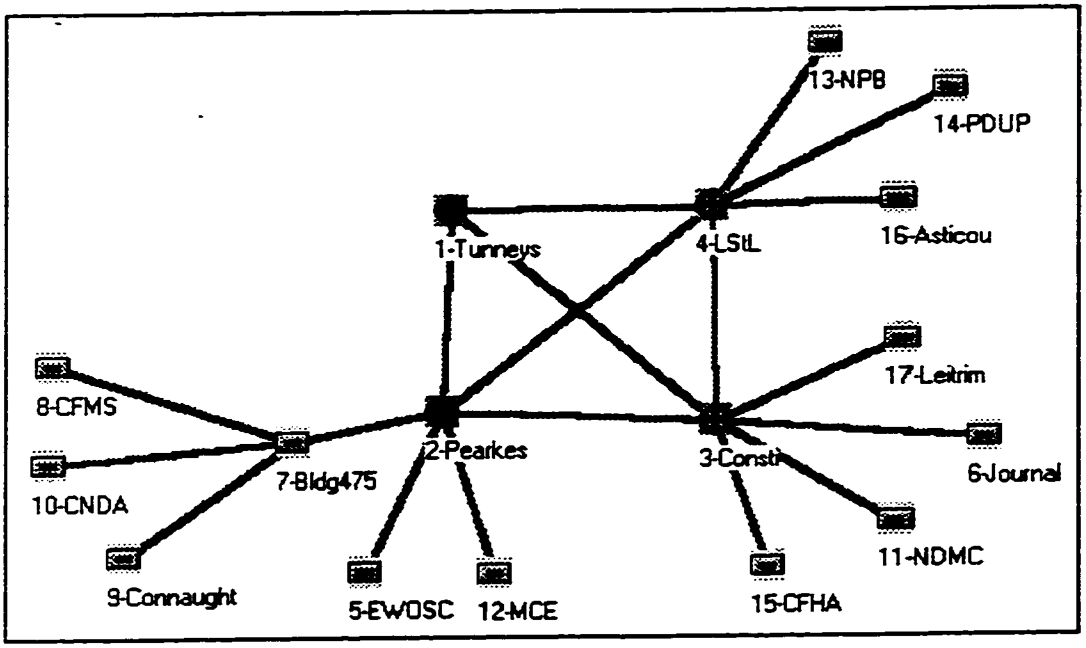


Figure 4-5: Final solution topology

The following subsections first provides an overview of the results and expected performance measures obtained, followed by a sensitivity analysis on these results and finally, a validation of these results is provided.

4.3.1. Overview

The intent of this subsection is to describe the solution obtained in terms of performance measures for each system component. Appendix E contains the detailed NDOT report for the final solution.

4.3.1.1. Links performance measures

The optimal solution has 35 T1s and 3 56kbps circuits and a total net present cost of $1,405,924. This solution cost can be broken down into a total sc of $58,400 and mrc of $39,760 for 36 months. Figure 4-6 illustrates how these facilities are distributed across the network. As expected the links between the four core buildings (in light grey) account for a significant amount of the total network capacity (i.e. 60%).

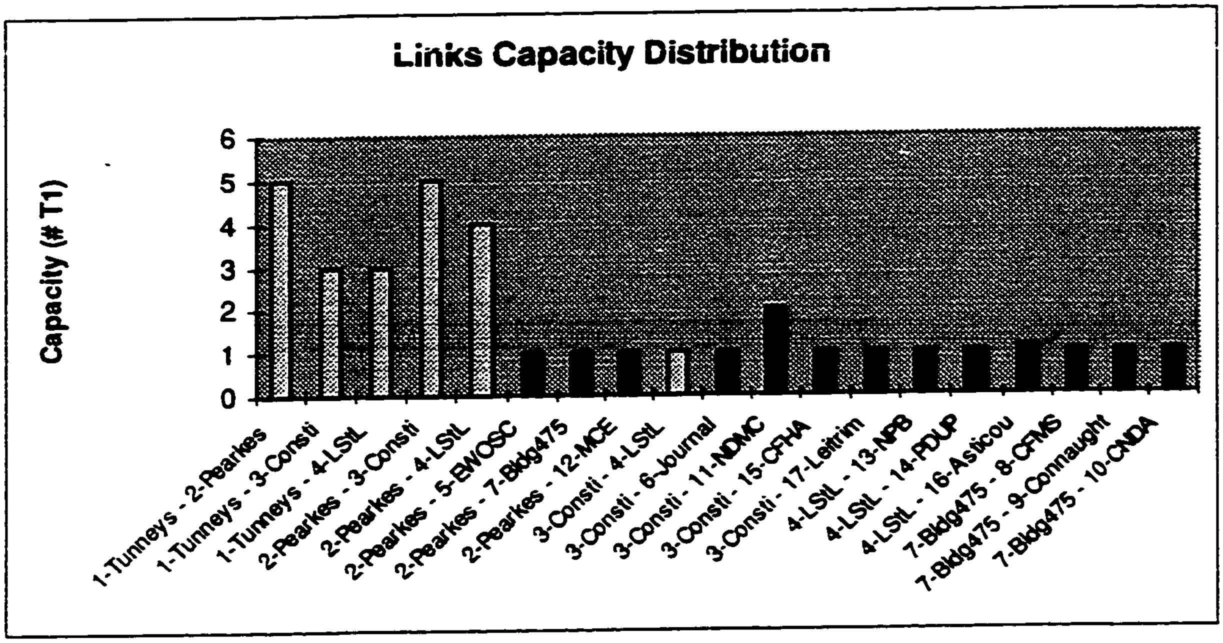


Figure 4-6: Links capacity distribution

The next interesting result is the expected utilisation of the network links under normal and failure conditions. As one would expect, the utilisation of non-survivable links (i.e. those links not strictly connecting two survivable nodes) is independent of the network state, simply because they were not subjected to failures and there is therefore no variation in the commodities transmitted on these links. Figure 4-7 illustrates the expected utilisation on those non-survivable links. Keeping in mind that the figures shown correspond to expected peak utilisation, link " 4-LStL - 16-Asticou" is worth scrutinising under an expected peak utilisation of 93%. This link is constituted of one T1 and three 56kbps facilities. Therefore, it is possible to replace the 3 56kbps facilities by a second T1 and significantly reduce the overall utilisation of the link by increasing its capacity by 80% at an increased total cost of less then 1%. Figure 4-8 illustrates the variations in utilisation for the survivable links based on the network state. Each group of bars represents a survivable link, while each colour represents a different failure scenario. For instance, the first orange bar represents the expected peak utilisation of the "1-Tunneys – 2-Pearkes" link with link "Pearkes - LStL" having failed. This graph clearly illustrates the significant impact of a failure on any survivable link. In fact, the average peak utilisation for these six links jumps from 40% under normal conditions to 61% under failure conditions.

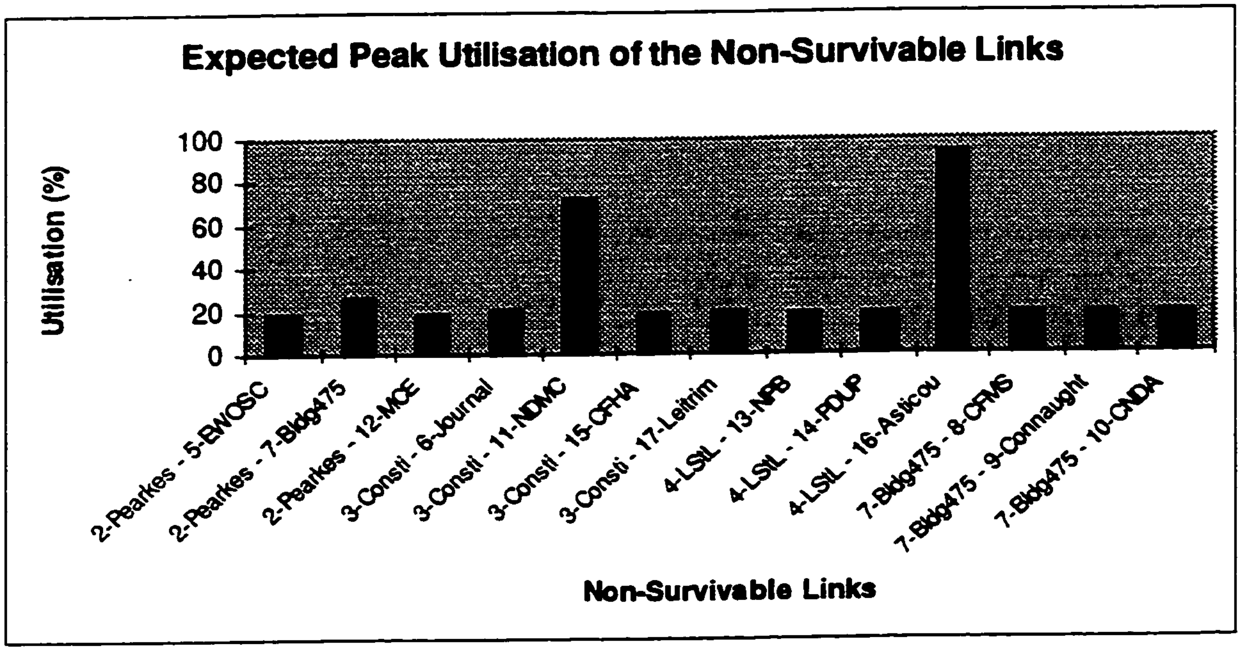


Figure 4-7: Expected peak utilisation for non-survivable links

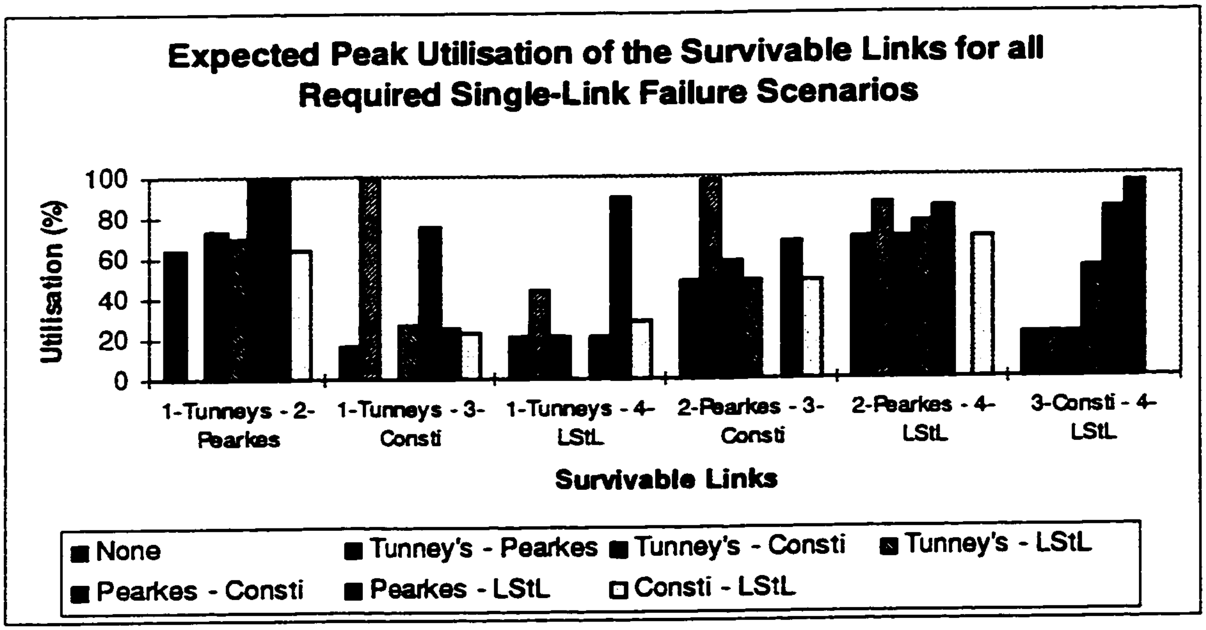


Figure 4-8: Expected peak utilisation of the survivable links for all required single-link failure scenarios

4.3.1.2. Nodes performance measures

The next results cover the expected performances of the network nodes (i.e. the building routers). As shown in Figure 4-9, the expected peak load on the non-survivable nodes is very low compared to their 50,000 pps capacity. But we have to keep in mind that only the inter-building backbone traffic was considered in this problem. This means that all the inner-building traffic using the building router to reach a separate IP network within that building was not considered. For that reason, it is more practical to look at the expected load on the routers in terms of actual throughput (pps) rather than in percentage of utilisation.

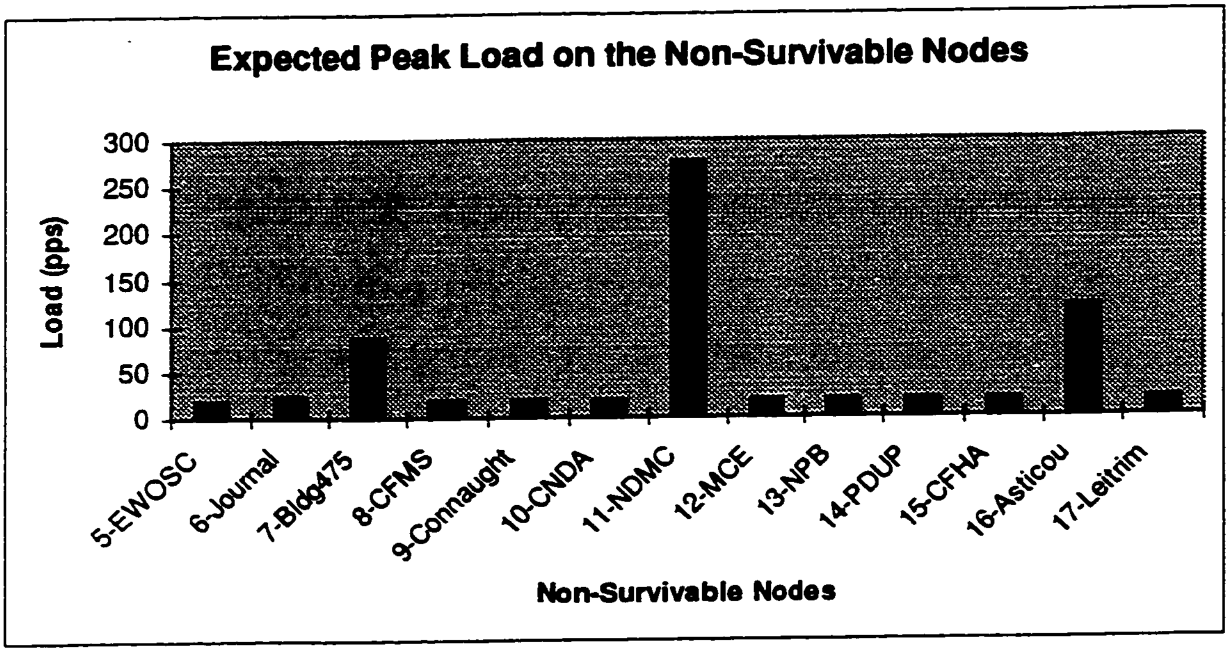


Figure 4-9: Expected peak load on the non-Survivable nodes

On the other hand, the survivable nodes are much more loaded than the non-survivable ones but, with a capacity over 100,000 pps, these inter-building loads are almost negligible. Figure 4-10 illustrates the slight variations in the load placed on each of these nodes for all required single-link-failure scenarios.

4.3.1.3. Commodity performance measures

Finally, one of the most important performance measure is the expected end-to-end delay for each commodity, as it confirms whether or not the performance objectives have been achieved. It is important to consider these measures for all single-link-failure scenarios. Figure 4-11 summarises these results in terms of averages and maximum expected ETED under the required failure scenarios. A more detailed bar chart for all commodities and for every required failure scenario is provided in Appendix F.

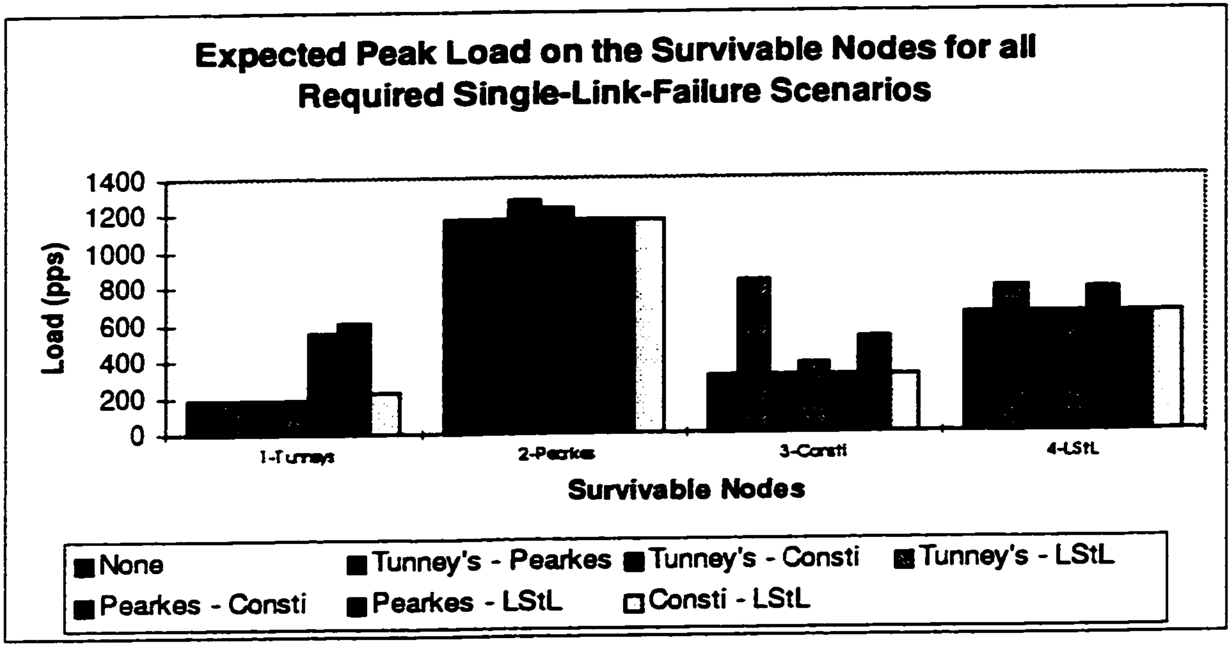


Figure 4-10: Expected peak load on the survivable nodes for all required single-link failure scenarios

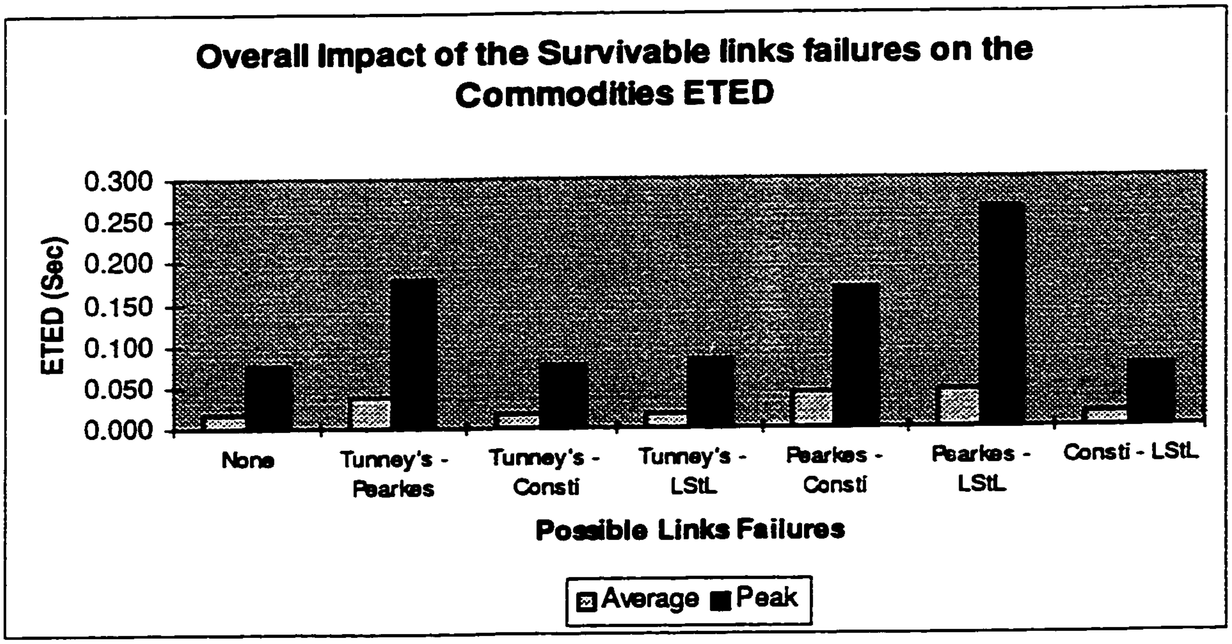


Figure 4-11: Overall impact of the survivable links failures on the commodities ETED

Because of the large amount of spare capacity required to support the failure of the survivable links, the expected performance of the network will be very good under normal conditions. In fact, a maximum expected peak ETED of 76 ms was achieved under normal conditions, compared to the 250 ms requirement derived in Chapter 3. Under failure conditions, their is only one instance where the ETEDR appears not to be met. More specifically, commodity "2-Pearkes – 4-LStL" has an expected maximum ETED of 265 ms (i.e. 15 ms above the required delay) when link "2-Pearkes – 4-LStL" fails (see Appendix E and/or F). Recalling the exercise conducted in Table 4-3, the reason for this value, which appears to violate Constraint (32) is explained by the fact that this commodity is routed via two paths and the delays from both paths were added when NDOT calculated the ETED. In fact, when looking at the paths taken (see Appendix E, page E-5), it is clear that the commodity is routed partially via "Pearkes-Consti-LStL" and "Pearkes-Tunneys-LStL". When using the delays associated with the links and nodes of the longest path (i.e. "Pearkes-Tunneys-LStL"), a corrected ETED of 127 ms is obtained, which does satisfy the ETEDR of the network.

4.3.2. Sensitivity analysis

The intent of this subsection is to analyse the sensitivity of the solution with respect to some of the key problem parameters. This is important to the decision maker, as it identifies the parameters for which accuracy may be important. For instance, the decision maker may learn that the accuracy of some parameters value is not required, since the solution is not (or negligibly) affected, no matter what the parameter value is. More specifically, this subsection focuses on the impact of δ (the proportion of traffic that needs to be supported under failure conditions), ps (the average packet size) and ETEDR.

4.3.2.1. Reservation parameter (δ)

This parameter represents the proportion of the traffic demands that has to be satisfied under failure conditions. As one would expect, the closer to 100 % the value of δ, the higher the cost of the solution will be. On the other hand, with a $\delta = 0$, the survivability requirement is simply eliminated, since no commodity has to be routed under failure conditions. As mentioned at the beginning of the subsection, this analysis is very useful to the decision maker, since it assigns a price estimate to the different level of survivability requirements. As shown in Figure 4-12, the net present cost of designing the network with 100% survivability is $1,405,924. Essentially, because of the non-linear shape of the curve, a large amount of survivability can be built in the network at a relatively low cost. With δ greater than 75 %, the slope becomes much steeper. Therefore these high survivability requirements need to be analysed further. Since we have a double objective, we also need to take a look at the impact of δ on the amount of traffic on the network. Essentially, Figure 4-13 illustrates that within certain intervals, the optimal flow distribution remains constant. Considering the combined influence of δ on the two objectives, the budget allocation and survivability requirement, the decision maker can select the most cost-effective value.

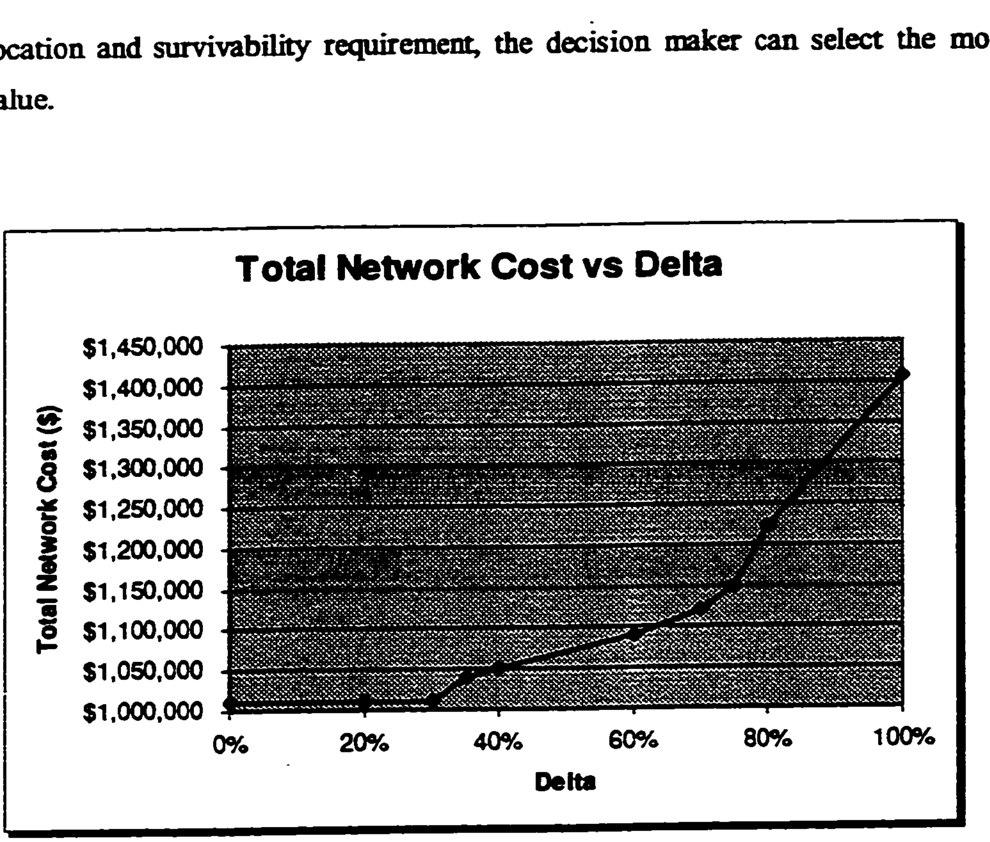


Figure 4-12: Impact of gamma on the total network cost

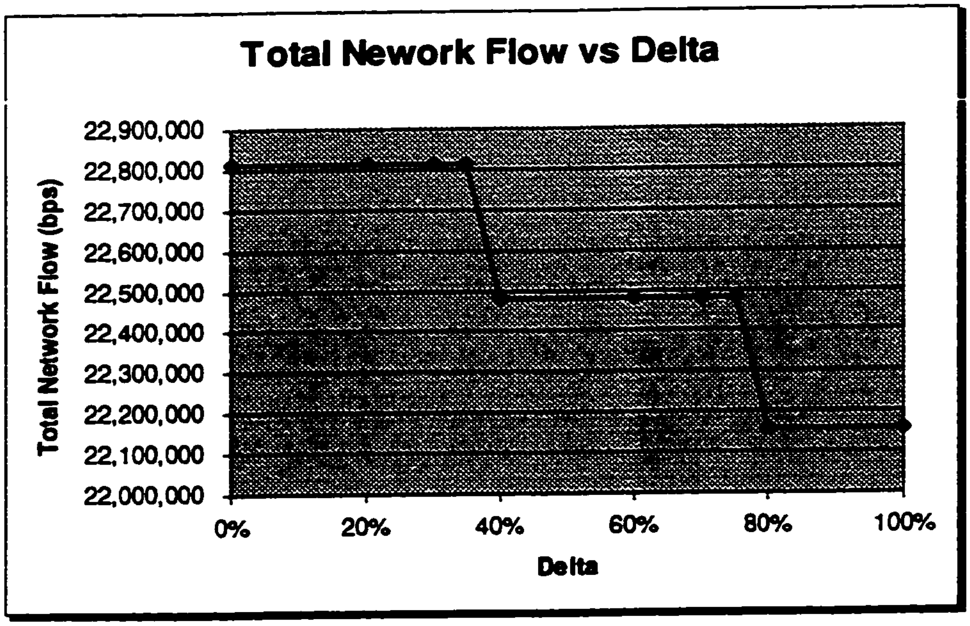


Figure 4-13: Impact of gamma on the total network flow under normal conditions

4.3.2.2. Packet size (ps)

Since all traffic coming on the backbone is Ethernet-based (IEEE 802.3), the maximum possible packet size is 1520 bytes (i.e. 1500 bytes per Ethernet frame + 20 bytes of IP overhead). The results obtained with several packet sizes demonstrate that it has absolutely no impact on the amount of traffic on the network and the solution cost varies by less than 1%, as shown in Figure 4-14. When analysing the different solutions in detail, we observe that these impacts on the solution produce minor modifications, such as moving one T1 from "Pearkes - Consti" to "Pearkes - LStL". This information is very useful because in practice, the packet size is not constant and these results tell us that the design solution obtained would behave well, no matter what the packet size is.

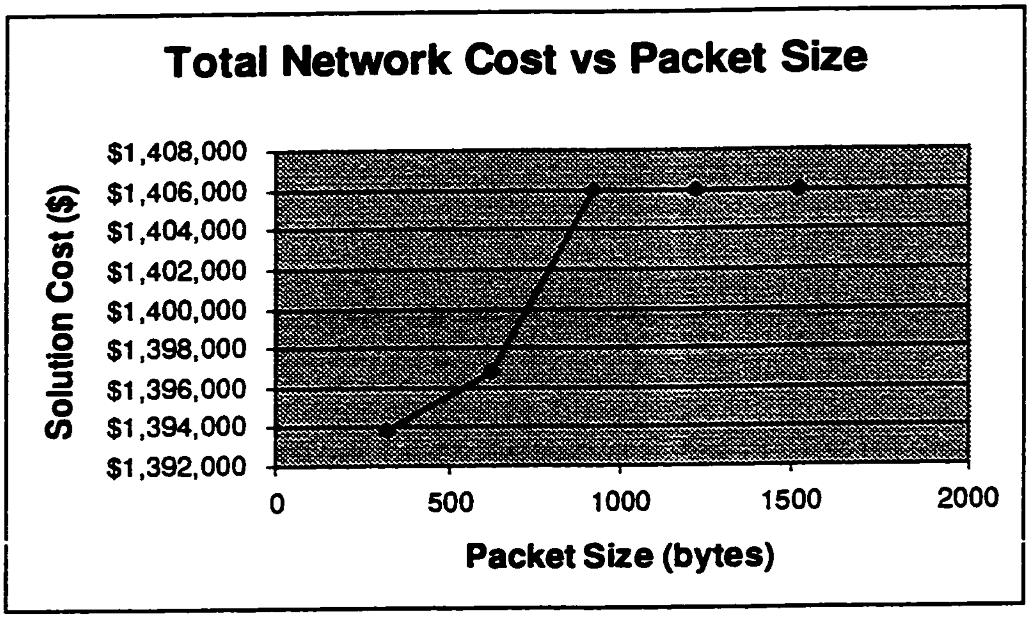


Figure 4-14: Impact of ps on the total network cost

4.3.2.3. End-to-end delay requirement (ETEDR)

In Section 3.2.3., we determined that the ETEDR had to be 250 ms for any commodity to travel from its origin to destination nodes. It is important for decision makers to know how sensitive the solution is to variations in the value of this parameter. For instance, they need to know if relaxing the ETEDR to 300 ms could translate into important savings.

The values of the R, ad_{ij} and nd_i parameters are interdependent according to Equation (26). To accomplish this analysis, nd_i was fixed at 0.001 sec, the lowest practical value, and R to 2. Then, only ad_{ij} had to be adjusted to reflect the different values analysed for ETEDR. Essentially, the total amount of flow on the network is not affected when varying the ETEDR, yet the solution cost is, as shown in Figure 4-15. This means that as the ETEDR becomes larger, the traffic is routed on the same links, but the number of facilities is reduced on some of the links.

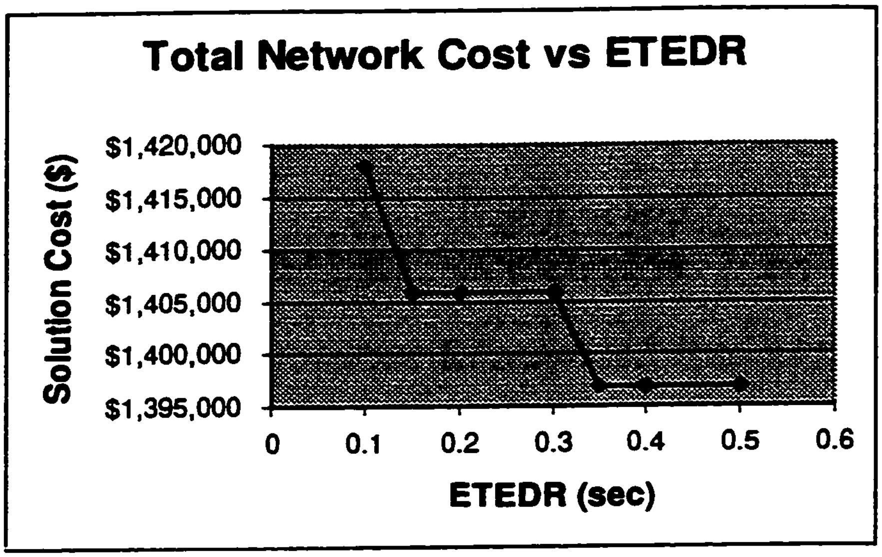


Figure 4-15: Impact of ETEDR on the total network cost

An interesting observation from Figure 4-15 is that even though the ETEDR was set to 250ms, the current solution yields an actual maximum ETED of 150ms. This can be explained by the fact that the survivability requirements are more restrictive than the ETEDR and require more spare capacity than required to satisfy the 250 ms ETEDR. Figure 4-15 also shows that the impact of this parameter on the solution cost is not very significant as it produces less than 2% variation.

4.3.3. Validation

The intent of this subsection is to assess the validity of the solution obtained. In other words, how well does the solution obtained satisfy the objective measures identified in Chapter 1 for the NDHQ MAN problem:

- ***Does the design solution obtained makes practical sense?*** Yes, given the data available. The model itself is believed to be relatively accurate, but for the reasons mentioned in the very first paragraph of this chapter, the results obtained can not be implemented as currently obtained. In any case, this question remains difficult to answer without live testing or simulation.

- ***Is the survivability requirement satisfied (Section 2.4.2)?*** Yes, the optimal solution obtained does ensure dual physical paths between the four core buildings and also ensures that sufficient spare capacity is provided on the backbone to support a single link failure between these core buildings.

- ***Is the performance requirement satisfied (Section 2.4.3)?*** Yes and exceeded. The optimal solution obtained ensures that the end-to-end delay for most possible IEEE 802.3 packet sizes will never exceed 150 ms under all operating conditions (see Figure 4-14).

- ***Is the design solution less expensive than the current one (Section 2.2.4)?*** This question is also difficult to answer because, if we blindly compare the mrc of the current network as of May 1997 ($37,630) with the optimal solution's ($39,760), we are comparing apples and oranges. The optimal solution has 17 nodes, it is 100% survivable between the four core buildings and considers a 150% annual growth for two years to reflect 1999 demands, compared with 33 nodes for the current design, unknown survivability provisioning and a traffic matrix reflecting 1997.

- ***Have we solved the important problems of the current network (Section 2.2.2)?*** Yes, the topology obtained (Figure 4-5) is much simpler than the current one (Figure 1-2 from May 1997). It can also be observed, when closely analysing the solution obtained (see Appendix E), that all commodities are expected to be routed over a single symmetric path under normal conditions.

Finally, it is worth mentioning that the full-mesh topology obtained between the four core buildings is influenced by the distance-independent facilities costs derived in Chapter 3. In fact, with a distance-dependent cost structure (as it is in reality), one would expect fewer links between the four core buildings to minimise the total distance covered between these buildings. One possible scenario would be a shortest length ring between the 4 core buildings.

Conclusion

We can now take a look at what was accomplished throughout this thesis, summarise its value and delineate potential future work to improve the decision support system, of which the model developed under this thesis is the corner stone.

Thesis summary

The intent of this thesis was to develop the required tools to solve a relatively comprehensive telecommunications network design optimisation problem. The base case application, from which the design requirements were derived, is the NDHQ MAN inter-building router backbone, where expensive leased facilities are installed to inter-connect building routers. Essentially, the problem tackled can be summarised as a Minimum Cost-Flow Capacitated Network Design Problem with multiple facilities, multiple commodities and constrained by performance and survivability requirements.

To solve this problem, a detailed definition of the problem was first carried out to identify all important elements of the problem. The solution methodology was then developed by integrating existing modelling and solution approaches obtained in the literature, with additional components specifically developed to address the requirements of this problem. The resulting model is supported by one mixed-integer/linear mathematical programming formulation. To support the numerical calculations involved, a 32-bit GUI-based network design tooi (NDOT) was developed. NDOT interfaces with the Cplex mathematical programming solver and automates most of the time-consuming tasks required to manipulate and convert the data between formats understandable by Cplex and meaningful to the network designer.

The methodology was tested and validated throughout its development with randomly generated networks from NDOT. Once satisfied with the settings of selected model parameters and the accuracy of the results obtained, the NDHQ MAN problem was solved. The optimality of the results obtained is mitigated by the elimination of some links from the list of candidates, prior to the solution of the problem, in order to reduce the size of the problem and support the survivability requirement of the problem. Nevertheless, the survivability and performance requirements were satisfied, joint optimisation of traffic routing, cost minimisation and arcs sizing was achieved and the resulting topology is much simpler to manage. These results were therefore interesting to analyse even if some of the data was unavailable and the target end-state of the system had changed.

Thesis value

The relative complexity of the problem and the realities of a practical scenario rendered this thesis very challenging. From a modelling perspective, considering both topological survivability and spare capacity planning in case of failures increased the problem size and complexity significantly. Also, the use of an M/M/1 queuing model to enforce performance requirements across the network certainly proved to be effective and surprisingly natural to integrate as a linear component of the model. At the implementation level, learning and using an object-oriented programming language such as Delphi, proved to be a very powerful automation and integration tool for the purpose of this thesis. Also, learning how to adjust the multitude of parameters available with Cplex proved to be very effective. Finally, the data collection effort required when attempting to solve live problems such as the NDHQ MAN certainly represents one of the important challenges faced throughout this thesis.

Future work/improvements

Finally, with design tools such as the one developed in this thesis, there is always room for improvement and it is important to identify these elements where improvement can be achieved by future work. The following paragraphs summarise the key areas identified for improvement, which cover the mathematical model, NDOT and the NDHQ MAN problem:

- At the time this thesis was initiated, dedicated circuits (such as T1s) appeared to be the solution of choice in a Metropolitan area. As a result of new technology development, much more cost-effective technologies have been introduced by the TSPs, such as ATM Private Virtual Circuits, ISDN, ADSL, and even Frame Relay. Therefore the integration of these technologies as possible options available by NDOT would make the tool much more flexible to meet today's requirements.

- An ambitious, but useful improvement would be to add a simulation module to NDOT for immediate validation of the design solutions obtained.

- Currently, NDOT interfaces with Cplex through a batch file, which executes Cplex and points to an input command file. This command file then tells Cplex how to solve the problem. Using the Cplex DLL, a seamless integration of the optimisation solver would be possible.

- The problem solved in this project only has 17 nodes. The reality is that most non-trivial network design problems comprise many more nodes. To effectively solve problems of the size that arise in telecommunications, an other research opportunity would be the development of good and fast heuristics based on Lagrangean relaxation, column generation, taboo search, etc.

- Improvement of the quality of the traffic matrix is essential to solve the NDHQ MAN problem accurately. This would include a thorough traffic analysis of all links on the current network and bandwidth requirements for those national applications soon to be deployed. Similarly, a detailed cost matrix for each facility would have to be developed to consider the distance impact on the facility leasing costs.

- The current performance model, based on the M/M/1 queuing model, assumes infinite buffer capacity for the routers, which does not reflect reality. In practice, buffer memory is limited and will be reached under congestion conditions; packets will then be dropped and required to be retransmitted, hence increasing end-to-end delay.

Additional possible improvements specific to NDOT are mentioned in Appendix B.

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Appendix A

Glossary

Capacity

- The ability to hold, receive, store, or accommodate. [Webster dictionary]
- In the context of this project it will be measured in bits per second (bps) and packet per seconds (pps) for links and nodes respectively.

Commodity

- A product; something useful or valuable; an economic good; [Webster dictionary]
- Either they represent distinct physical goods, or more frequently, they are used to model Origin-Destination (OD) pairs. [Gendron *et al*, 1996]

Core vs satellite buildings

- As part of the consolidation project, four of the NDHQ buildings have been selected as core buildings. That is, they will lodge the majority of the NDHQ population. The four core buildings are Major-General Pearkes Building, Constitution Building, Louis St-Laurent Building and Building 16 in Tunney's Pasture.
- On the other hand, satellite buildings are the remaining ones which are used for special purposes.

Directed and undirected arcs/graphs

- An undirected arc is one for which the direction is not required. In other words, arc (i,j) is equivalent to arc (j,i).
- A directed arc on the other hand is one for which direction is important. For instance, a traffic flow would be represented by a directed arc, since the direction of the flow is important.
- A directed graph is composed of directed arcs only, while an undirected graph is composed of undirected arcs.

Facility

- Something that is built, installed, or established to serve a particular purpose; [Webster dictionary]
- In telecommunications, facilities provide high bandwidth point-to-point connections, each of them transmitting information at different rates [Gendron *et al*, 1996]

Lagrangean relaxation

In Lagrangean Relaxation, some of the constraints are replaced by adding terms to the objective function. The added terms form a penalty for violating the removed constraints and the optimal solution to the relaxed problem is a bound on the value of the optimal solution to the original problem [Kershenbaun, 1993].

Network states

The states of the network are used to model each possible failures in the network. Each state is important, since the network will react differently to each failures. $s=0$ means that all network components (nodes and links) are operational and $s\neq0$ means that component s (a link or a node) has failed.

***NP*-hard**

A class of problems, known as non-deterministic polynomial time -or class-*NP* -problems, that may not necessarily be solvable in polynomial time, but the actual solutions to which may be tested for correctness in polynomial time [http://www.cna.org/isaac/glossb.htm].

Polyhedral combinatorics

This important topic, in applied mathematics, is the study of integer polyhedra (i.e. polyhedra with integer extreme points). [Ahuja *et al*, 1993].

Problem relaxation

When relaxing a problem, it is possible to remove some constraints or replace the objective function by another (presumably simpler) function, which bounds the optimum value [Kershenbaun, 1993].

Reliability

Reliability is the probability that a network functions according to a specification [Lloyd *et al*, 1995]

Router

- A level three Internet Protocol packet switch. Formerly called a gateway in much of the IP literature [Moy, 1994].
- In the context of this thesis, the router is the actual switching device found in each building or node. The terms node, building and routers will be used interchangeably when referring to the actual nodes of the network graph.

Survivability

Survivability is the ability of a network to perform according to a specification after it has been damaged. Under certain assumptions, survivability means 100% reliability. [Lloyd *et al*, 1995]

π-connected

A network is π-connected if each demand pair has at least π disjoint paths. A set of disjoint paths is one where there are no vertices or edges in common between any of the paths except the origin and destination vertices. If two paths are edge-disjoint, they have no edges in common. If two paths are vertex-disjoint, they have no vertices in common. Being vertex-disjoint is stronger than being edge-disjoint. If two paths are vertex-disjoint, they are also edge-disjoint, since two paths could not share an edge without sharing the vertices that terminate that edge. A π-connected network, $\pi \geq 2$, is survivable. If there are π-1 distinct failures, then at most π-1 paths can be affected, since no failure can affect more than one path. Therefore, with up to π-1 failures, we are guaranteed at least one unaffected path for each demand pair and all communication attempts will be successful. [Lloyd *et al*, 1995]

Appendix B

Network Design Optimisation Tool

Table of content

List of figures

1. Overview

NDOT is a telecommunication network design software tool with manual and automated design capabilities. It has been developed using the 32-bit Delphi Object-Oriented Development Environment and provides a Graphical User Interface (GUI). The main purpose of the tool is to automate the design optimisation model developed for this thesis, but it comprises many additional capabilities. The following sections will provide detailed information about the main features of the tool.

2. Display capabilities

NDOT provides a GUI with standard functionality such as pull-down menus, node drag capabilities, objects can be clicked for additional information, etc. Figure B-1 shows the NDOT GUI.

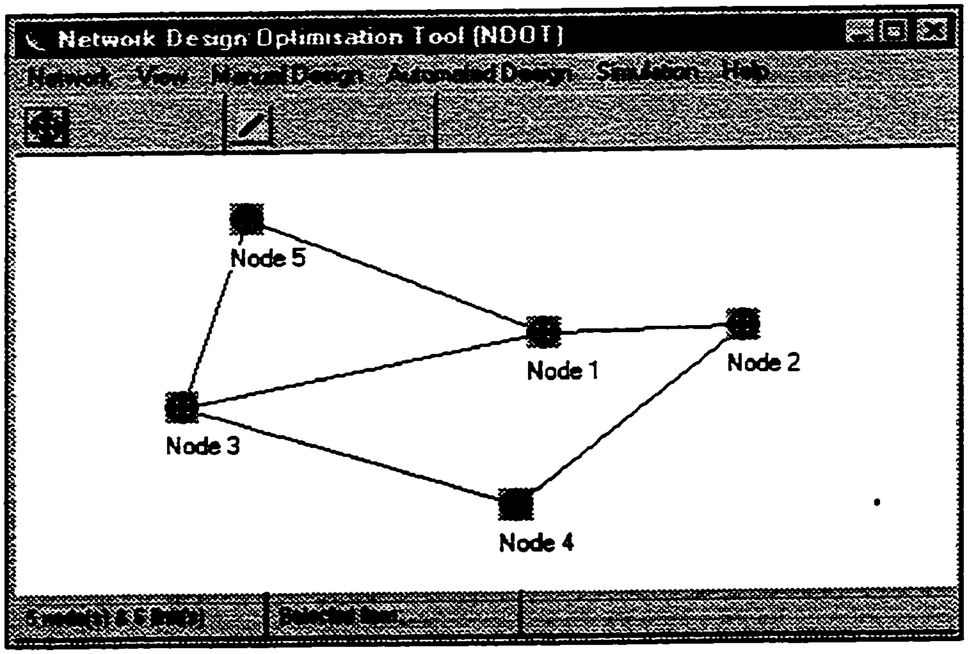


Figure B-1 – NDOT graphical user interface

3. Manual design capabilities

In its most simple mode, NDOT supports manual network design. The user can either access the "Manual Design" pull-down menu or click on one of the speed buttons below the menu bar. As shown in Figure B-2, the user can add, delete or modify a link or a node. The speed buttons replicate the "Add Node" and "Add Link" functions otherwise available under the "Manual Design" pull-down menu.

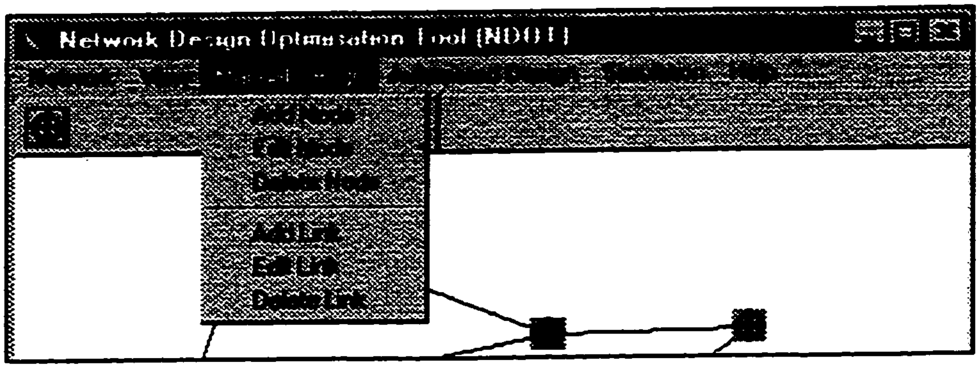


Figure B-2 – Manual design options

4. Automated design capabilities

The objective of a network design tool such as NDOT is to automate and integrate tasks that are usually done manually. This section describes the three main categories of automated design capabilities offered by NDOT:

- A Random Network Generator (RNG) has been developed mainly as a validation tool for the other design procedures and algorithms implemented;
- Some basic optimisation algorithms were implemented in the early development stages of NDOT for experimentation purposes. They are the well-known Minimum Spanning Tree [Prim, 1957] and the Shortest Path [Dijkstra, 1959] algorithms, and;
- The third automated design module supports the implementation of the mathematical model developed in Chapter 2 of the main document.

Figure B-3 illustrates these options.

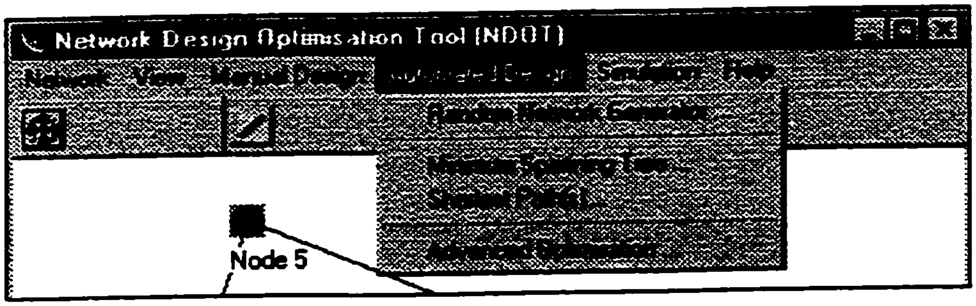
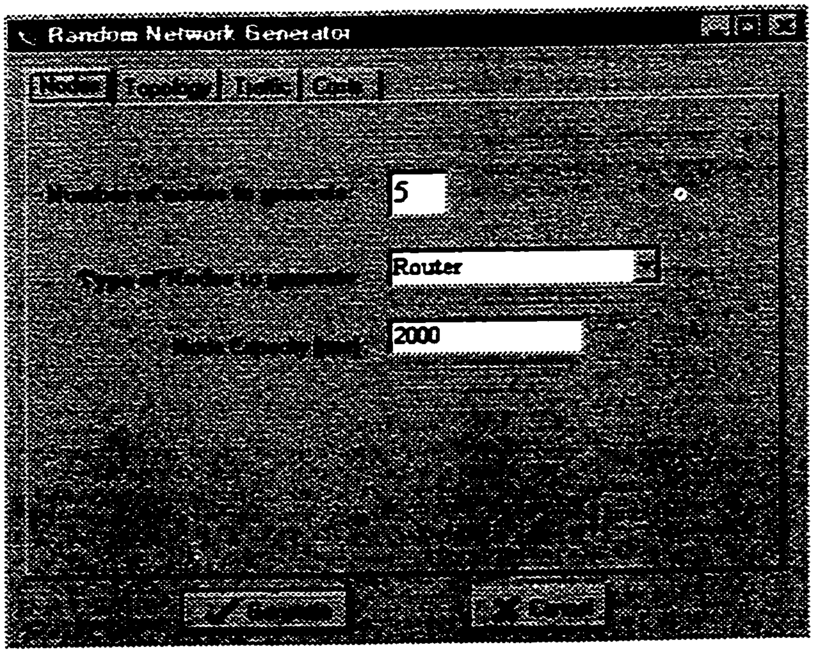


Figure B-3 – Automated design options

4.1. Random network generation

The Random Network Generator (RNG) has several sub-components. Its minimum support is to generate random locations for the desired number of nodes, node type and processing capacity (see Figure B-4). The remaining categories (i.e. Topology, Traffic and costs) are optional.



5

Router

2000

Figure B-4 – Random network generator (nodes settings)

The next option available to the user is the generation of a random topology. After a selection of choices in the topology setting sheet (see Figure B-5), links will be randomly generated, while ensuring that the user's requirements are satisfied. For instance, if a user wants to generate a connected partially meshed network of 5 nodes, it suffices to select the appropriate radio button and the desired total number of links to be generated. As a radio button is selected, the upper and lower bounds for the number of links that can be generated are automatically calculated. The lower bound, in this case, ensures that enough links will be generated to obtain a connected network (i.e. nn-1) and the upper bound limits the total number of links to a full-mesh topology (i.e. nn*(nn-1)/2), where nn is the desired number of nodes that is selected from the nodes setting sheet.

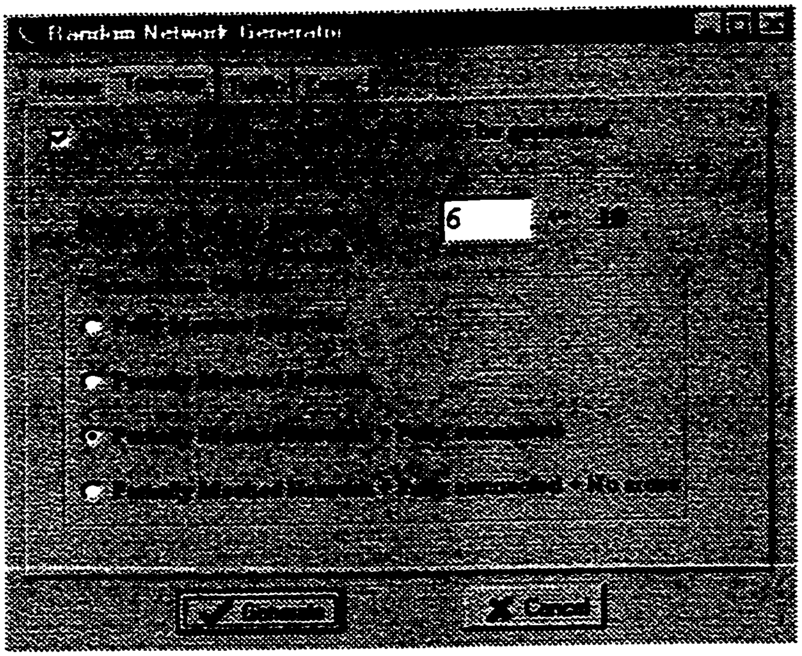
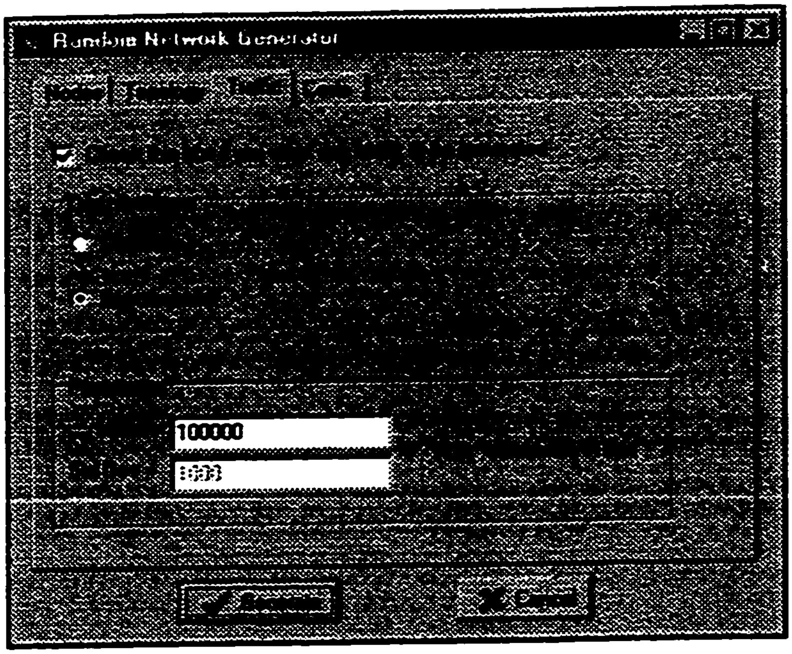


Figure B-5 – Random network generator (topology settings)

The third sheet (see Figure B-6) offers options on the generation of the traffic matrix (i.e. traffic demands between nodes). At this time, only two distribution modes have been implemented, a uniform and an exponential distribution. The adequacy of such distributions to represent a real network traffic matrix may be questioned; yet, the purpose of the RNG was to quickly generate complete networks, which could be used to develop, validate and mostly debug the implementation of the optimisation algorithms.

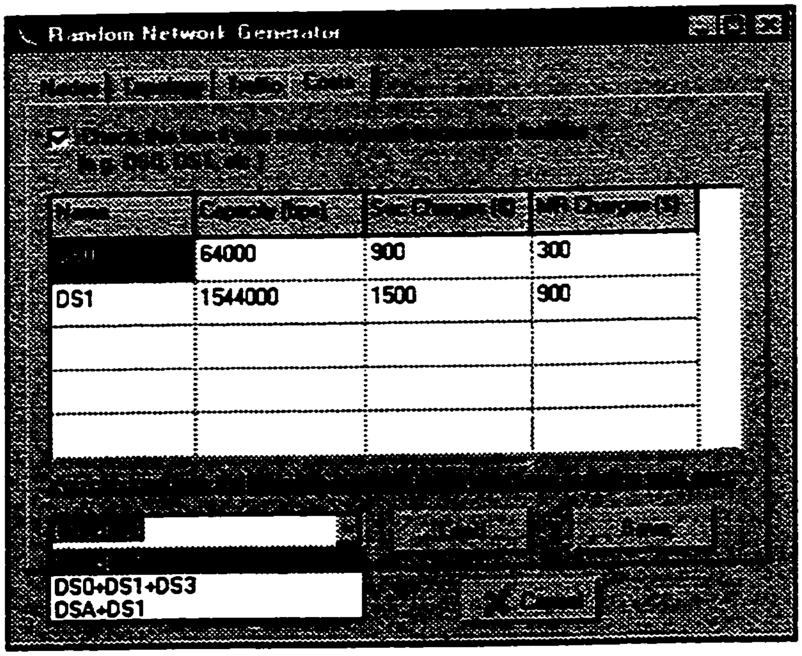
Finally, the last sheet provides options on the links cost structure that will be used. As shown in Figure B-7, users can either define their own cost structure for each facility type or load an existing one from file. NDOT uses two small record files to support this capability. Worth mentioning is the fact that this component of the RNG is not random, but is included to provide the capability to generate complete networks in one step.



100000

[illegible]

Figure B-6 – Random network generator (traffic settings)



Name	Capacity (bps)	[illegible]	[illegible]
[illegible]	64000	900	300
DS1	1544000	1500	900

DS0+DS1+DS3
DSA+DS1

Figure B-7 – Random network generator (costs settings)

4.2. Basic optimisation

The first optimisation algorithms implemented in NDOT were the Minimum Spanning Tree (MST) algorithm from Prim [1957] and the Shortest Path (SP) algorithm from Dijkstra [1959]. As currently implemented, the MST algorithm minimises the total distance required to connect all the nodes of the network. The distance measure used reflects the physical location of the nodes on the network graph. Figure B-8 shows an example of the MST applied to a 40-node network.

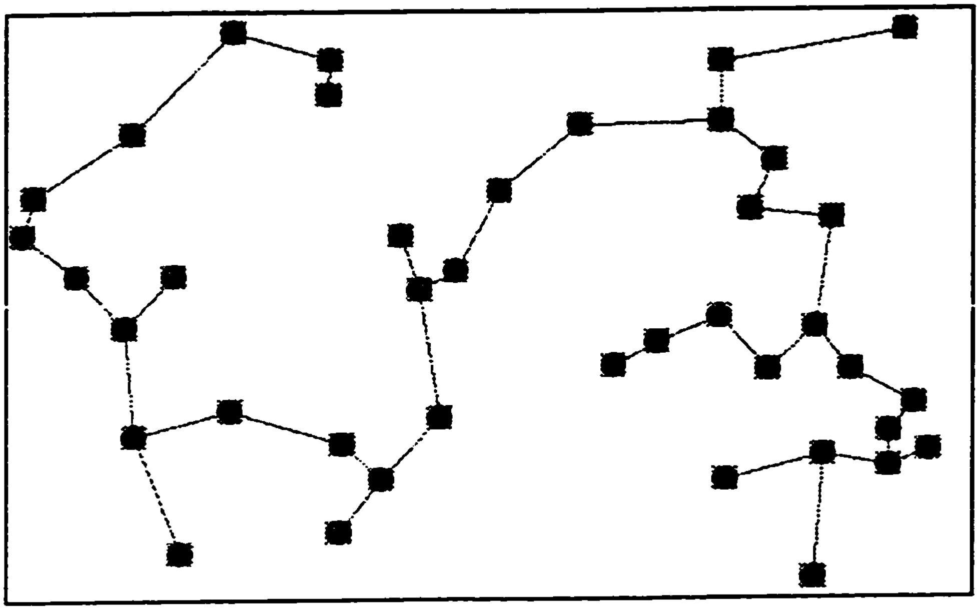


Figure B-8 – Minimum spanning tree example

Similarly, the SP algorithm identifies the shortest path(s) between a pre-selected origin node and destination node(s) using existing links. Although fundamentally similar, the key difference between these two algorithms is that the MST considers the entire set of nodes, while the SP algorithm requires that the origin and destination nodes be designated in the same connected graph. As an example, Figure B-9 shows the result graph for the Dijkstra algorithm seeking the shortest path between Nodes 2 and 7.

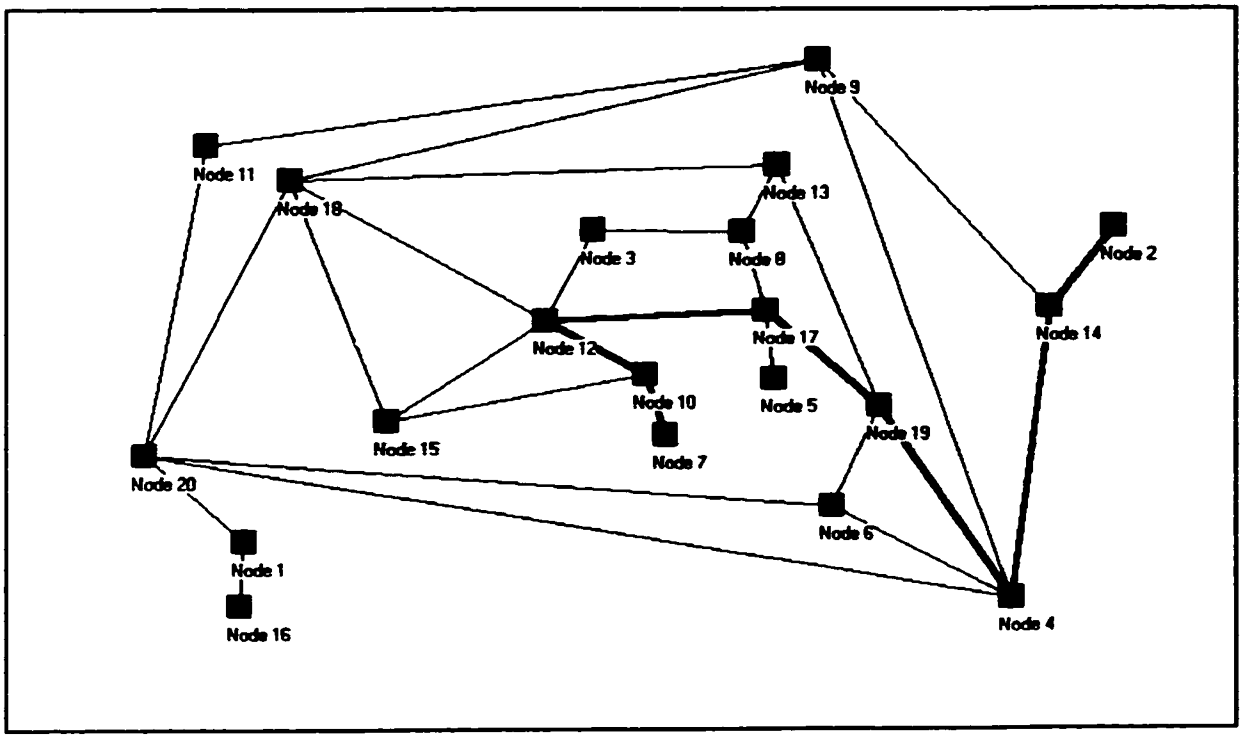


Figure B-9 – Shortest path example

4.3. Advanced optimisation

This module is the core of NDOT. It implements the model developed in Chapter 2 of the thesis. The following two subsections describe the Cplex-NDOT integration and the parameters settings available to the user.

4.3.1. Cplex-NDOT integration

The engine behind the advanced design optimisation capability of NDOT is Cplex 6.0, an MS-DOS-based linear optimisation solver. When solving a problem, NDOT will first take an input file, which includes node capacities and a traffic matrix as well as a second file containing the link costs. Through a set of forms, the user will then set all required problem parameters. All this information will then be recorded as the data of a MIP formulation to be read by Cplex. Cplex will then solve the MIP problem and generate a solution file. This solution file is then read by NDOT and converted to a more meaningful report and network graph. Figure B-10 illustrates the interactions between NDOT and Cplex.

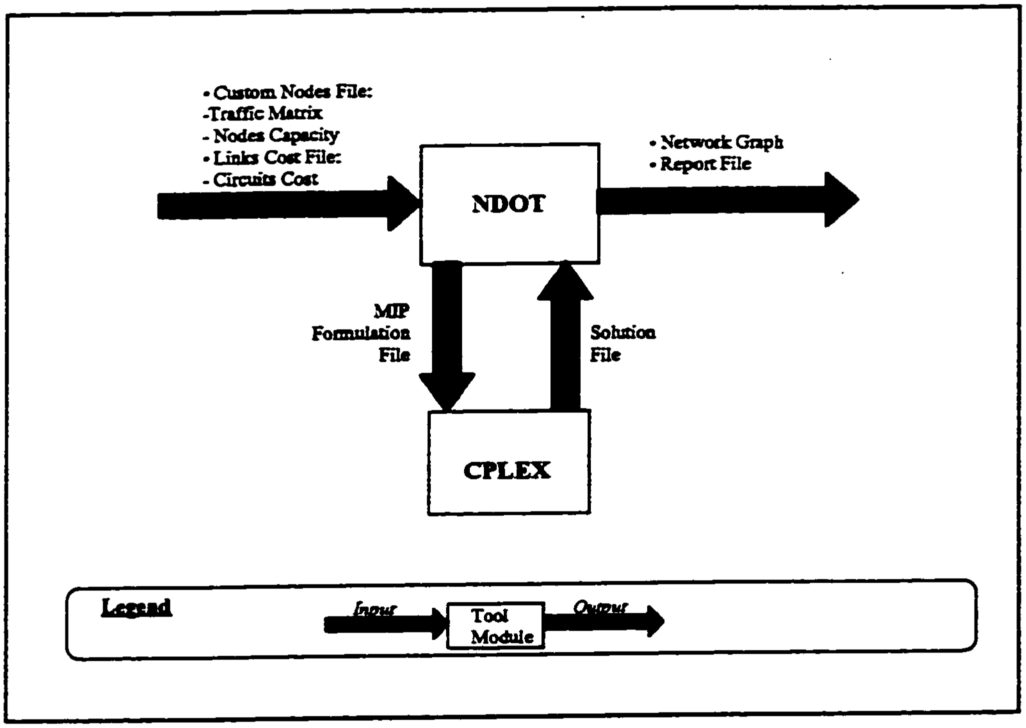
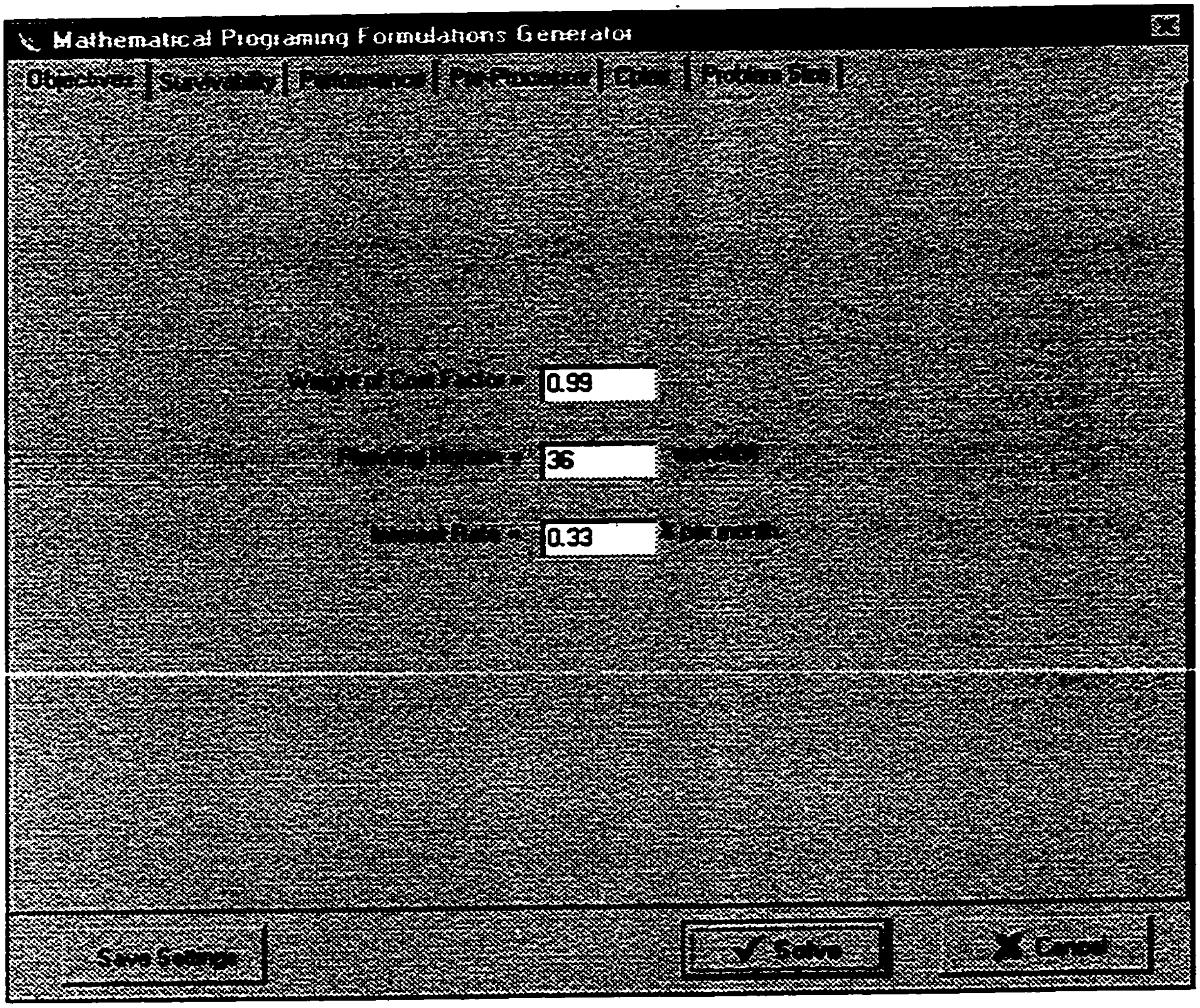


Figure B-10: Cplex-NDOT integration

4.3.2. Parameter settings

This module allows the user to configure all the necessary problem parameters. For instance, a comparison between the design solutions with and without survivability constraints can be easily accomplished. Such capability, for instance, would allow the decision-maker to associate a cost to the survivability requirement of the network. The "Save Settings" button, at the bottom of the form, allows the user to save all its parameter settings so they can be kept with the problem file and do not have to be re-entered every time the problem is loaded. This is especially useful when several links and facilities are eliminated manually through the pre-processor sheet (see Figure B-16). The next paragraphs will go through each screen of settings and explain their potential influence on the design solutions.

The first screen allows the user to set the objective parameters. As illustrated in Figure B-11, the user can select the weight factor associated with the economical components of the objective function (α), the planning horizon (ph) (i.e. number of fix-length periods) considered in the problem and the interest rate per period (ir). More specifically, α sets the relative importance of each objective component (i.e. minimum cost solution vs shortest paths solution). The following two parameters ph and ir are required for the calculation of the Net Present Value (NPV) of the solution cost (see Section 3.2. from the thesis report for more details).



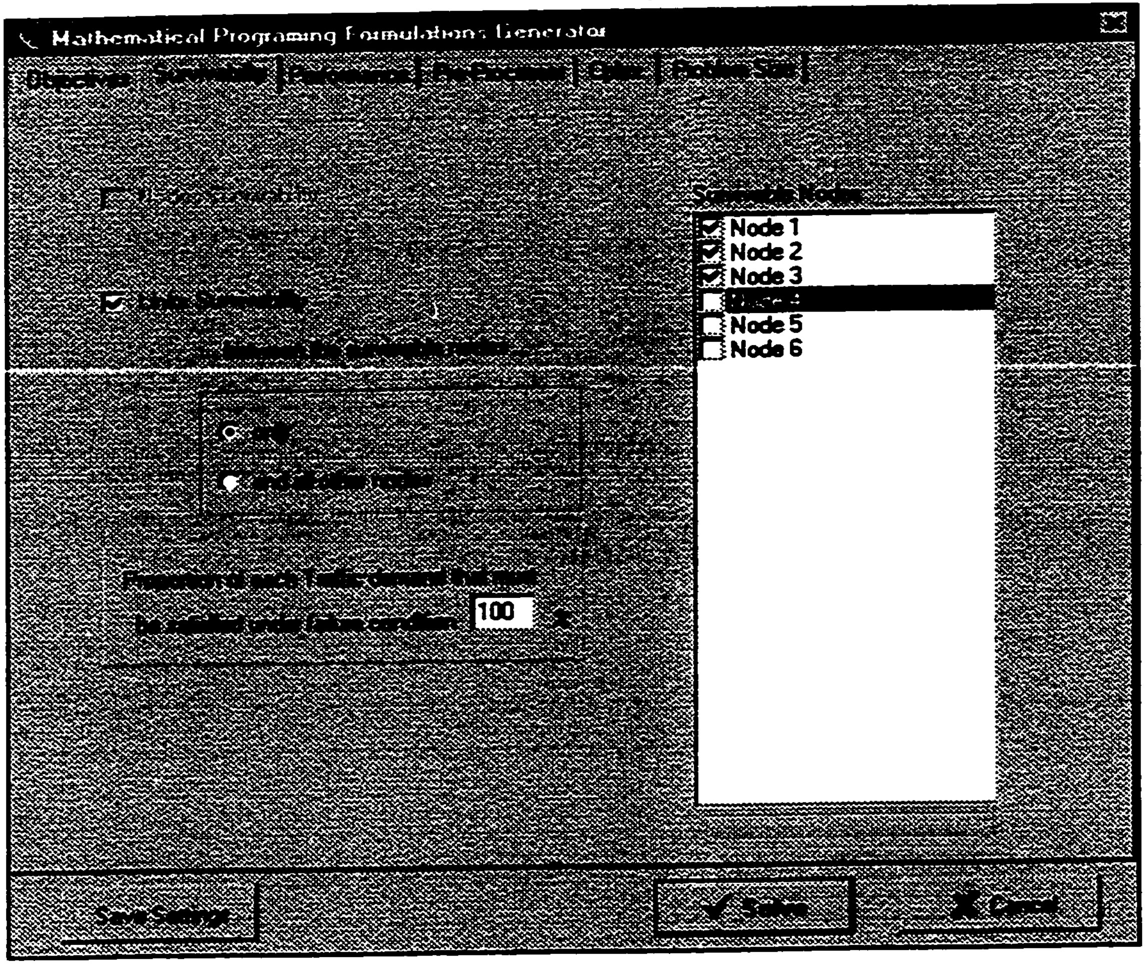
Weight of Cost Factor = 0.99

Planning Horizon = 36 months

Interest Rate = 0.33 % per month

Figure B-11: Objective function settings

The second screen, illustrated in Figure B-12, allows the user to set all the necessary survivability parameters. More specifically, the user can select the survivable nodes from the list, identify the exact proportion of the traffic demands that need to be supported under failure conditions and select the extent of survivability considerations (i.e. link or node survivability). If the link survivability option is selected, then is survivability required strictly between the survivable nodes or it can be achieved through the other nodes of the network? Figure B-13 and B-14 illustrate both cases respectively. In Figure B-13, survivability is enforced only between the 3 survivable nodes (Nodes 1, 2 and 3), while in Figure B-14, survivability between these 3 nodes is achieved through the other nodes of the network. The second case is less restrictive and results in potentially cheaper and more survivable solutions, but can significantly impact the size of the problem, since the number of possible links failure (and therefore network states) increases significantly.



☑ Links Survivability

between the survivable nodes ...

○ only

● and all other nodes

Proportion of each Traffic demand that must be satisfied under failure condition: 100 %

Survivable Nodes

☑ Node 1
☑ Node 2
☑ Node 3
☐ Node 4
☐ Node 5
☐ Node 6

Figure B-12: Survivability settings

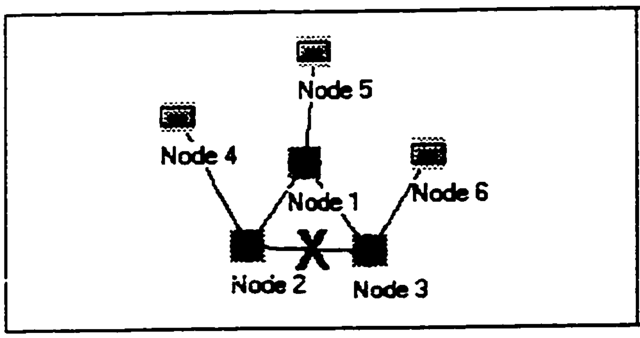


Figure B-13: Survivability between survivable nodes only

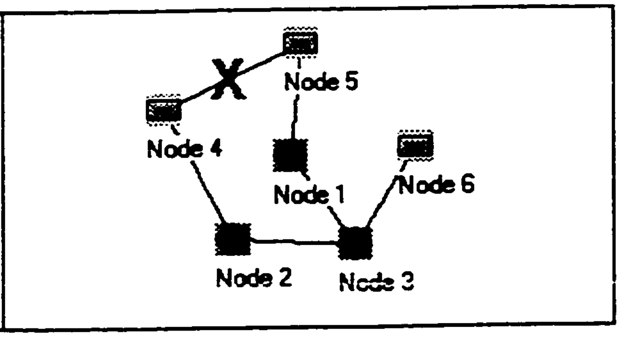


Figure B-14: Survivability between survivable nodes and all other nodes

The third screen (see Figure B-15), allows the user to set the performance requirements that need to be satisfied. More specifically, the user has the flexibility to identify the average packet size expected on the network, the end-to-end delay requirement for all commodities and the arc and node delay limitation parameters. For more details on how these parameters interact, the reader is referred to Section 3.2. of the thesis report.

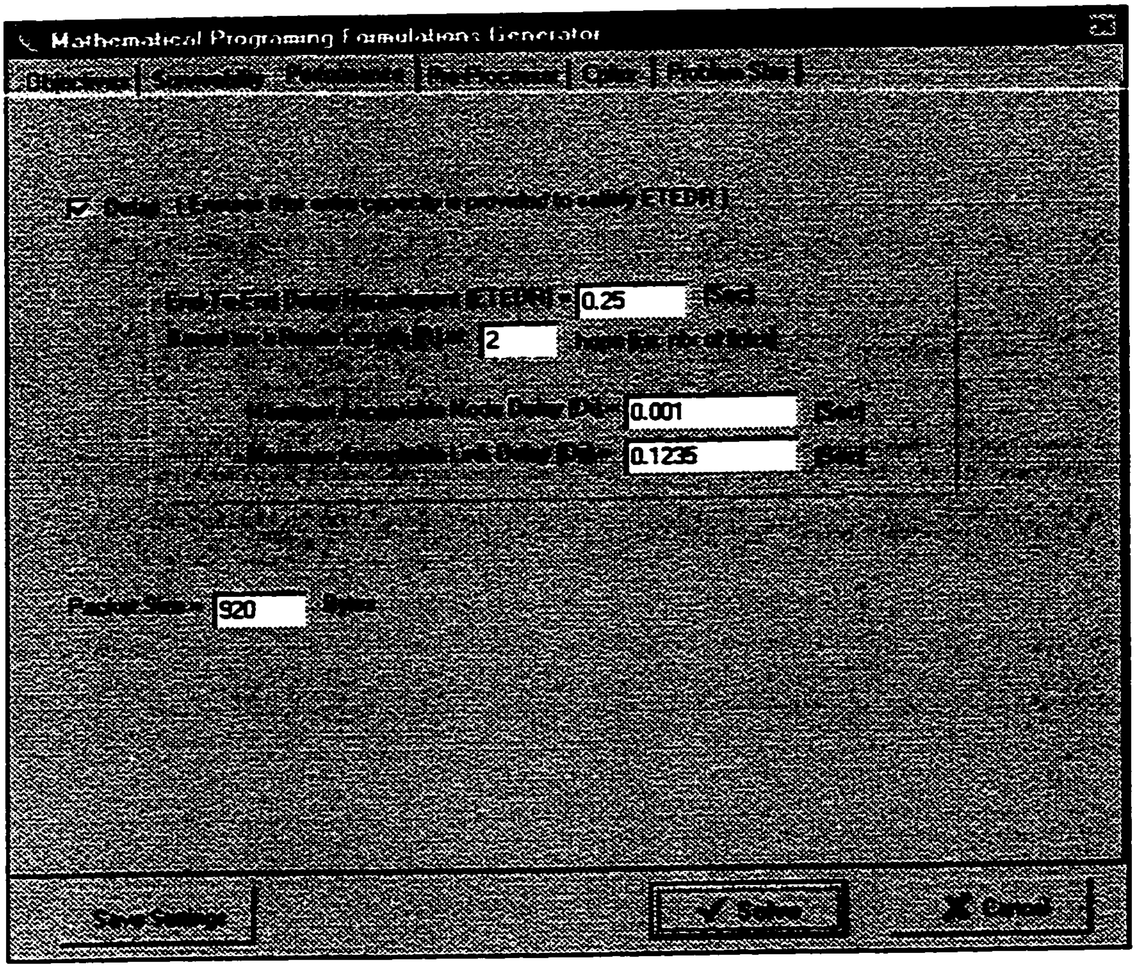
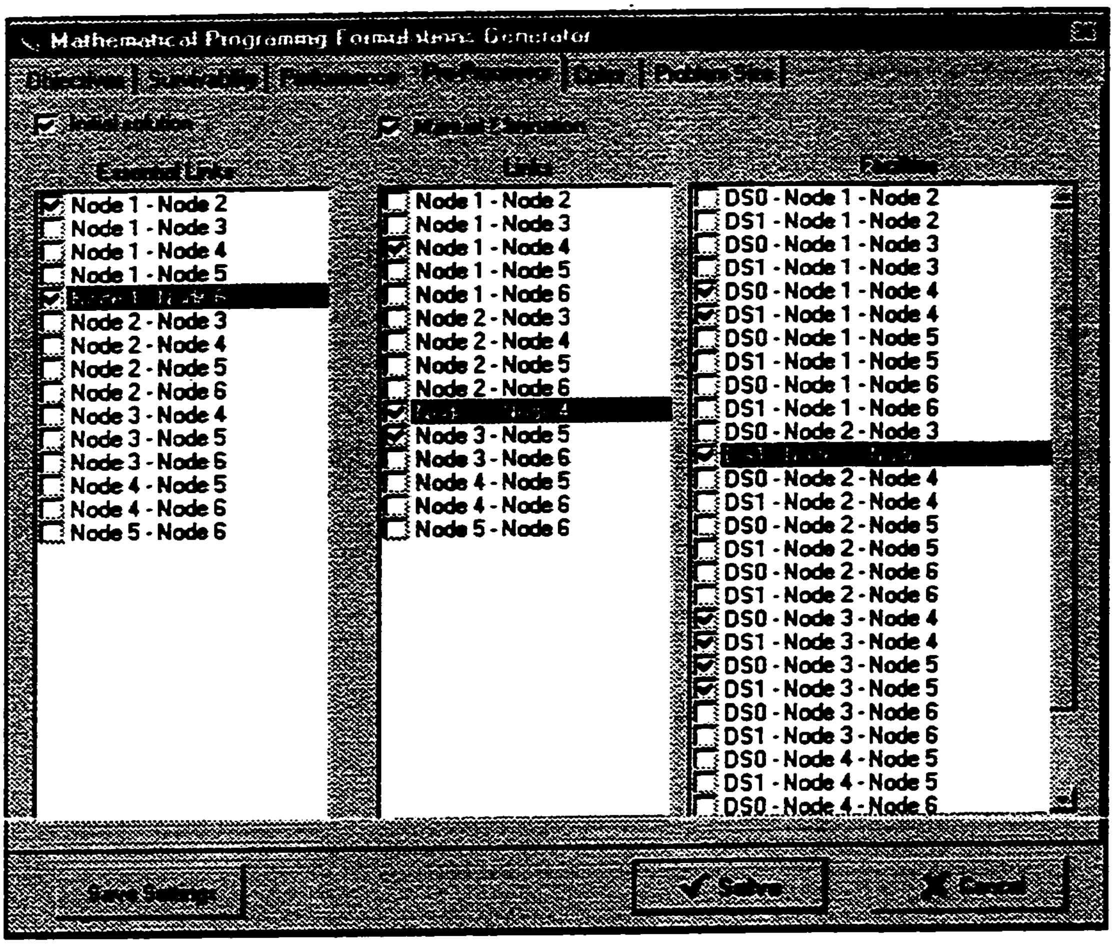


Figure B-15: Performance settings

The fourth screen (Figure B-16), supports manual configuration of the pre-processor. Basically, the user can manually identify which links must absolutely be part of the solution and which links and facilities should not be part of the final solution. For instance, the first option can be used to take into account factors not considered by the model. On the other hand, by carefully analysing the traffic matrix, some links and facilities can be eliminated as solution candidates, which can significantly reduce the size of the problem without affecting the optimality of the solution.

The fifth screen allows the user to select a specific solution strategy, by adjusting some of the Cplex parameters. In particular, one of the important parameters is the "mipgap", which allows the user to set the relative sensitivity to variations of the optimal value. Finally, the last sheet provides figures on the actual size of the problem being solved and the impact of the pre-processor in the reductions of the number of variables and constraints.



☑ Initial solution

Essential Links

- ☑ Node 1 - Node 2
- ☐ Node 1 - Node 3
- ☐ Node 1 - Node 4
- ☐ Node 1 - Node 5
- ☑ Node 1 - Node 6
- ☐ Node 2 - Node 3
- ☐ Node 2 - Node 4
- ☐ Node 2 - Node 5
- ☐ Node 2 - Node 6
- ☐ Node 3 - Node 4
- ☐ Node 3 - Node 5
- ☐ Node 3 - Node 6
- ☐ Node 4 - Node 5
- ☐ Node 4 - Node 6
- ☐ Node 5 - Node 6

Links

- ☐ Node 1 - Node 2
- ☐ Node 1 - Node 3
- ☑ Node 1 - Node 4
- ☐ Node 1 - Node 5
- ☐ Node 1 - Node 6
- ☐ Node 2 - Node 3
- ☐ Node 2 - Node 4
- ☐ Node 2 - Node 5
- ☐ Node 2 - Node 6
- ☑ Node 3 - Node 4
- ☑ Node 3 - Node 5
- ☐ Node 3 - Node 6
- ☐ Node 4 - Node 5
- ☐ Node 4 - Node 6
- ☐ Node 5 - Node 6

Facilities

- ☐ DS0 - Node 1 - Node 2
- ☐ DS1 - Node 1 - Node 2
- ☐ DS0 - Node 1 - Node 3
- ☐ DS1 - Node 1 - Node 3
- ☑ DS0 - Node 1 - Node 4
- ☑ DS1 - Node 1 - Node 4
- ☐ DS0 - Node 1 - Node 5
- ☐ DS1 - Node 1 - Node 5
- ☐ DS0 - Node 1 - Node 6
- ☐ DS1 - Node 1 - Node 6
- ☐ DS0 - Node 2 - Node 3
- ☑ DS1 - Node 2 - Node 3
- ☐ DS0 - Node 2 - Node 4
- ☐ DS1 - Node 2 - Node 4
- ☐ DS0 - Node 2 - Node 5
- ☐ DS1 - Node 2 - Node 5
- ☐ DS0 - Node 2 - Node 6
- ☐ DS1 - Node 2 - Node 6
- ☑ DS0 - Node 3 - Node 4
- ☑ DS1 - Node 3 - Node 4
- ☑ DS0 - Node 3 - Node 5
- ☑ DS1 - Node 3 - Node 5
- ☐ DS0 - Node 3 - Node 6
- ☐ DS1 - Node 3 - Node 6
- ☐ DS0 - Node 4 - Node 5
- ☐ DS1 - Node 4 - Node 5
- ☐ DS0 - Node 4 - Node 6

Figure B-16: Pre-processor settings

5. Reporting capabilities

With the amount of information generated in a problem solution, it is important to have an effective reporting capability to highlight the key results. For instance, when reviewing the results of an advanced optimisation problem, the user will be interested in an illustration of the solution topology, performance measures, paths of the commodities, link and node statistics (e.g. expected utilisation and delay) and a summary of the parameter settings for comparison purposes. NDOT graphically represents the solution topology and provides additional results through an ASCII file accessible via the "View" and "Report" pull-down menu and menu item respectively. At the time of writing, integration of text and various graphics in a single report file was being developed. These various graphics will provide the capability to effectively summarise expected network performance results, such as the representation of expected utilisation of all network links in one chart.

6. Import / export capabilities

Several file formats are available to store problem data. For instance, one can store the node and link data separately or on the same file. A file format was also added to store node and link data in a database format (i.e. csv) for ease of transfer between NDOT and a spreadsheet or database software. Finally, the actual picture of the network graph can be exported as bitmap graphic file if desired.

7. Printing capabilities

NDOT currently offers the capability to print the network graphs as displayed on the application main screen, the ASCII report and the help file.

8. Help capabilities

At this time, the only help capability is an ASCII file accessible through the "Help" pull-down menu. Again, the intent is to convert that file into an SGML-based help file.

9. Conclusion

A tool such as NDOT has several potential usage aimed at a company or organisation (such as a Telecommunication Services Provider or DND) that wants to inter-connect several sites with point-to-point communication facilities (e.g. leased lines). Fundamental design problem revolves around how the sites should be inter-connected and at what speed. Therefore, NDOT could be used by a company/organisation focusing its efforts on network planning to maintain an optimal backbone. A typical question is to determine whether the current network architecture should be modified when a new corporate application is deployed throughout the company. Such addition brings about an increase in the traffic requirement between affected sites and may result in a different optimal network architecture. Different scenarios like this one can be analysed with NDOT.

Finally, since NDOT was developed as needs were identified, several of its modules can be improved. The following summarises potential improvements to the tool to make it a more robust and effective design optimisation tool:

- There is a definite requirement to rationalise the number of file formats available for import/export capabilities. In other words, a single file format to store problem information (i.e. network generic data, link data, node data, commodities information, optimisation settings, etc.) would be much easier to maintain and use.

- As mentioned in Section 6, the current ASCII-based reporting capability has limitations. To take advantage of the inherent information capability of graphics, it is essential that the current reporting method be replaced by a more powerful reporting engine such as ReportSmith.
- As mentioned earlier, NDOT's data structure was implemented as needs surfaced. Even though some rationalisation occured throughout the development to ensure satisfactory execution performance, the application's object structure should be rationalised and reorganised as the requirements are much clearly defined. This would significantly clarify the source code, which would improve its execution speed and ease future developments.
- As currently developed, NDOT is based on a static memory model. In other words, no matter what the size of the problem is, NDOT will always require the same amount of memory. The solution is to implement a dynamic memory model using pointers instead of fixed-length arrays to hold data.
- Once a large help file is developed, it would be desirable to support it in SGML format.
- An ambitious endeavour would be to integrate a simulation module to better validate the optimal solutions generated by the advanced design optimisation module.
- Currently, to solve an optimisation problem with Cplex, NDOT executes a batch file, which in turn executes Cplex with a command file as input. This command file tells Cplex how to solve the problem, where to get the formulation file and where to generate the results file. Cplex is also available as a 32-bit DLL, which allows a much more seamless integration into the controlling application.
- Finally, from a GUI perspective, the capability to zoom in/out would allow larger networks to be displayed and worked on. Also, if a simulation module (or design capabilities within buildings networks) were developed, the capability to define and view different levels of the network (i.e. inter-buildings backbone, inner-building backbone, etc.) would become essential.

Appendix C

Overview of the OSPF routing protocol

This appendix is intended to provide the reader with an overview of the Open Shortest Path First (OSPF) routing protocol used on the NDHQ MAN network. This overview was extracted from Section 1.1. of RFC 1583 [Moy, 1994].

OSPF routes IP packets based solely on the destination IP address and IP Type of Service (TOS) found in the IP packet header. IP packets are routed "as is", they are not encapsulated in any further protocol headers as they transit the Autonomous System. OSPF is a dynamic routing protocol. It quickly detects topological changes in the AS (such as router interface failures) and calculates new loop-free routes after a period of convergence. This period of convergence is short and involves a minimum of routing traffic.

In a link-state routing protocol, each router maintains a database describing the Autonomous System's topology. Each participating router has an identical database. Each individual piece of this database is a particular router's local state (e.g., the router's usable interfaces and reachable neighbours). The router distributes its local state throughout the Autonomous System by flooding.

All routers run the exact same algorithm, in parallel. From the topological database, each router constructs a tree of shortest paths with itself as root. This shortest-path tree gives the route to each destination in the Autonomous System. Externally derived routing information appears on the tree as leaves.

OSPF calculates separate routes for each Type of Service (TOS). When several equal-cost routes to a destination exist, traffic is distributed equally among them. The cost of a route is described by a single dimensionless metric.

OSPF allows sets of networks to be grouped together. Such a grouping is called an area. The topology of an area is hidden from the rest of the Autonomous System. This information hiding enables a significant reduction in routing traffic. Also, routing within the area is determined only by the area's own topology, lending the area protection from bad routing data. An area is a generalisation of an IP subnetted network.

OSPF enables the flexible configuration of IP subnets. Each route distributed by OSPF has a destination and mask. Two different subnets of the same IP network number may have different sizes (i.e., different masks). This is commonly referred to as variable length subnetting. A packet is routed to the best (i.e., longest or most specific) match. Host routes are considered to be subnets whose masks are "all ones" (0xffffffff).

All OSPF protocol exchanges are authenticated. This means that only trusted routers can participate in the Autonomous System's routing. A variety of authentication schemes can be used; a single authentication scheme is configured for each area. This enables some areas to use much stricter authentication than others.

Externally derived routing data (e.g., routes learned from the Exterior Gateway Protocol (EGP)) is passed transparently throughout the Autonomous System. This externally derived data is kept separate from the OSPF protocol's link state data. Each external route can also be tagged by the advertising router, enabling the passing of additional information between routers on the boundaries of the Autonomous System.

Appendix D

Description of selected Cplex parameters

This appendix is intended to provide the reader with a description of the Cplex parameters that were adjusted in Subsection 3.2.5. of the main document. All of this information was extracted from the Cplex 6.0 documentation used for this thesis.

Parameter	Possible Values	Description
Set preprocessing presolve	Yes or no	This indicator, when set to yes, will invoke Cplex Presolve to make problem simplifications and reductions.
Set preprocessing coeffreduce	0: none 1: reduce only to integral coefficients 2: reduce all possible coefficients	Coefficient reduction is a technique used when pre-solving mixed integer programs. The benefit is to improve the objective value of the initial (and subsequent) linear programming relaxation solved during branch-and-bound by reducing the number of non-integral vertices. However, the linear programs generated at each node may become more difficult to solve. There is a resulting trade-off between reducing the number of nodes in the branch-and-bound tree and the time to solve each node via a linear programming algorithm. Full coefficient reduction reduces all possible coefficients, while integer coefficient reduction will only reduce coefficients to integer values.

Set preprocessing relax	Yes or no	This indicator, when set to yes, will invoke the Cplex Presolve for linear programs for the initial relaxation of a mixed integer program, according to the other Cplex Presolve parameter settings. Sometimes additional reductions can be made beyond any MIP presolve reductions that may have already been done.
Set mip strategy rootheuristic	-1: do not use a heuristic 0: automatically determined 1: use a rounding heuristic at node 0	The value of this parameter determines which heuristic should be applied to develop an integer solution. Setting the value to 1 indicates that a rounding heuristic at the fist node, Node 0, should be used. Setting the value to 0, the default, indicates that the decision on using a heuristic will be automatically determined by looking at the solution of the initial relaxation of the problem.
Set mip strategy nodeselect	0: depth-first search 1: best-bound search 2: best-estimate search 3: alternate best-estimate search	This parameter is used to set the rule for selecting the next node to process when backtracking (proceeding back through the tree when a node is infeasible, or cut-off, or judged unpromising) The depth-first search strategy chooses the most recently created node. The best bound strategy chooses the node with the best objective function for the associated LP relaxation. Th best estimate strategy selects the node with the best estimate of the integer objective value that would be obtained from a node once all integer infeasibilities are removed. An alternate best-estimate search is also available.

Set mip strategy variableselect	-1: branch on variable with minimum infeasibility 0: branch variable automatically selected 1: branch on variable with maximum infeasibility 2: branched based on pseudo reduced costs 3: strong branching	This parameter is used to set the rule for selecting the branching variable at the node which has been selected for branching. The maximum infeasibility rule chooses the variable with the largest factional value; the minimum infeasibility rule (setting of –1) may lead more quickly to a first integer feasible solution, but will usually be slower overall to reach the optimal integer solution. The maximum infeasibility rule (setting 1) forces larger changes earlier in the tree, which tends to produce faster overall times to reach the optimal integer solution. Pseudo-reduced costs (setting 2) causes variable selection based on pseudo-costs which are derived from pseudo-shadow prices. Strong branching (setting 3) causes variable selection based on partially solving a number of sub-problems with tentative branches to see which branch is the most promising. This strategy can be effective on large, difficult MIP problems. The default value of 0 allows Cplex to select the best rule based on the problem and its progress.
Set mip strategy branch	-1: down branch selected first 0: algorithm decides 1: up branch selected first	This parameter is used to decide which branch, the up branch of the down branch, should be taken first at each node. If a specific variable has been assigned a branching direction using and ORD file, the ORD file specification will override the BRANCH parameter for this variable.

Set mip strategy mipgap	0 – 1.0	This parameter is used as a relative tolerance on the gap between the best integer objective and the objective of the best node remaining. When the value abs(best node – best integer) / (1.0 + abs(best node)) falls below the value of the MIPGAP parameter setting, the mixed integer optimisation is stopped.
Set mip strategy startalgorithm	1: primal simplex 2: dual simplex 3: network simplex 4: barrier with crossover 5: dual simplex to iter. limit, then barrier 6: barrier without crossover	The value of this parameter determines which LP algorithm should be used to solve the initial relaxation of the MIP.
Set mip strategy subalgorithm	1: primal simplex 2: dual simplex 3: network optimiser fol. by dual simplex 4: barrier with crossover 5: dual simplex to iter. limit, then barrier 6: barrier without crossover	This parameter sets the algorithm to be used on sub problems. At the default setting of 2, dual simplex is used on sub problems.

Set mip strategy dgradient	0: Determined automatically; 1: Standard dual pricing 2: Steepest-edge Pricing 3: Steepest-edge Pricing in slack space 4: Steepest-edge Pricing, unit initial norms	This parameter selects the pricing algorithm for 'TRANOPT' (dual simplex). While the default pricing usually provides the fastest solution time, many problems benefit from alternate settings
Set mip strategy pgradient	-1: Reduced-cost Pricing; 0: Hybrid reduced-cost and Devex Pricing; 1: Devex Pricing 2: Steepest-edge Pricing 3: Steepest-edge Pricg w slack initial Norms 4: Full Pricing	This parameter selects the pricing algorithm for 'PRIMOPT' (primal simplex). While the default pricing usually provides the fastest solution time, many problems benefit from alternate settings.
Set mip strategy netfind	1, 2, or 3	This parameter establishes the level of network extraction for network simplex optimisations using 'NETOPT'. At the default setting of 1, only the pure network is extracted. At settings 2 and 3, larger networks are extracted using reflection scaling and general scaling, respectively.

Appendix E

Extracts of NDOT report for the final solution

```
Network Design Optimisation Tool (NDOT)
Optimisation Report - 12/9/98 - 7:34:21 PM


*************************************
**        SUMMARY INFORMATION      **
*************************************
The Total cost of the design solution is 1405924 $.
The design solution contains 19 links.
Total flow on the network with no link failure = 22155300 bps.
Total flow on the network with link "1-Tunneys - 2-Pearkes" failed = 27051300 bps.
Total flow on the network with link "1-Tunneys - 3-Consti" failed = 22895100 bps.
Total flow on the network with link "1-Tunneys - 4-LStL" failed = 23130000 bps.
Total flow on the network with link "2-Pearkes - 3-Consti" failed = 25873200 bps.
Total flow on the network with link "2-Pearkes - 4-LStL" failed = 26841690 bps.
Total flow on the network with link "3-Consti - 4-LStL" failed = 22490100 bps.



*************************************
**       PARAMETERS SETTINGS       **
*************************************
> Objective Function:
   - Alpha = 0.99
   - ph = 36 periods
   - ir = 0.33 % per period
> Survivability:
   - Survivable Nodes: 1-Tunneys, 2-Pearkes, 3-Consti, 4-LStL,
   - Gamma = 100 %
> Performance:
   - ps = 920 Bytes
   - ETEDR = 0.25 Sec
   - R = 2
   - nd = 0.001 Sec
   - ad = 0.1235 Sec
> Cplex:
   - mipgap = 0.01
```

```
*************************************
**        LINKS INFORMATION        **
*************************************
===================================
Link: 1-Tunneys - 2-Pearkes
===================================
5 X 1544000 Bps Facilitie(s) @ 1115 $ each
Total Capacity:  7720000 Bps.
 * Network State = 0 => no link failure.
    -Total Flow(Bps)---Utilisation(%)---Expected Delay(Sec)-
        4896000              63.4197            0.0026062322946174З

    -(>)--Demand Pair----Flow(Bps)------
      1-Tunneys > 2-Pearkes        414000

    -(<)--Demand Pair----Flow(Bps)------
      2-Pearkes > 1-Tunneys        4482000

 * Network State = 1 => Link "1-Tunneys - 2-Pearkes" has failed.
   N/A

 * Network State = 2 => Link "1-Tunneys - 3-Consti" has failed.
    -Total Flow(Bps)---Utilisation(%)---Expected Delay(Sec)-
        5635800              73.0026            0.00353133096631808

    -(>)--Demand Pair----Flow(Bps)------
      1-Tunneys > 2-Pearkes        414000
      1-Tunneys > 3-Consti        417600
      1-Tunneys > 11-NDMC       900

    -(<)--Demand Pair----Flow(Bps)------
      2-Pearkes > 1-Tunneys        4482000
      3-Consti > 1-Tunneys        320400
      11-NDMC > 1-Tunneys       900

 * Network State = 3 => Link "1-Tunneys - 4-LStL" has failed.
    -Total Flow(Bps)---Utilisation(%)---Expected Delay(Sec)-
        5368500              69.5402            0.00312991707420807

    -(>)--Demand Pair----Flow(Bps)------
      1-Tunneys > 2-Pearkes        414000

    -(<)--Demand Pair----Flow(Bps)------
      2-Pearkes > 1-Tunneys        4482000
      4-LStL > 1-Tunneys       325800
      16-Asticou > 1-Tunneys        146700

 * Network State = 4 => Link "2-Pearkes - 3-Consti" has failed.
    -Total Flow(Bps)---Utilisation(%)---Expected Delay(Sec)-
        7660405              99.228            0.123500293648817

    -(>)--Demand Pair----Flow(Bps)------
      1-Tunneys > 2-Pearkes        414000
      3-Consti > 2-Pearkes        288505
      3-Consti > 7-Bldg475        41400
      6-Journal > 2-Pearkes        28800
      11-NDMC > 2-Pearkes       6300
```

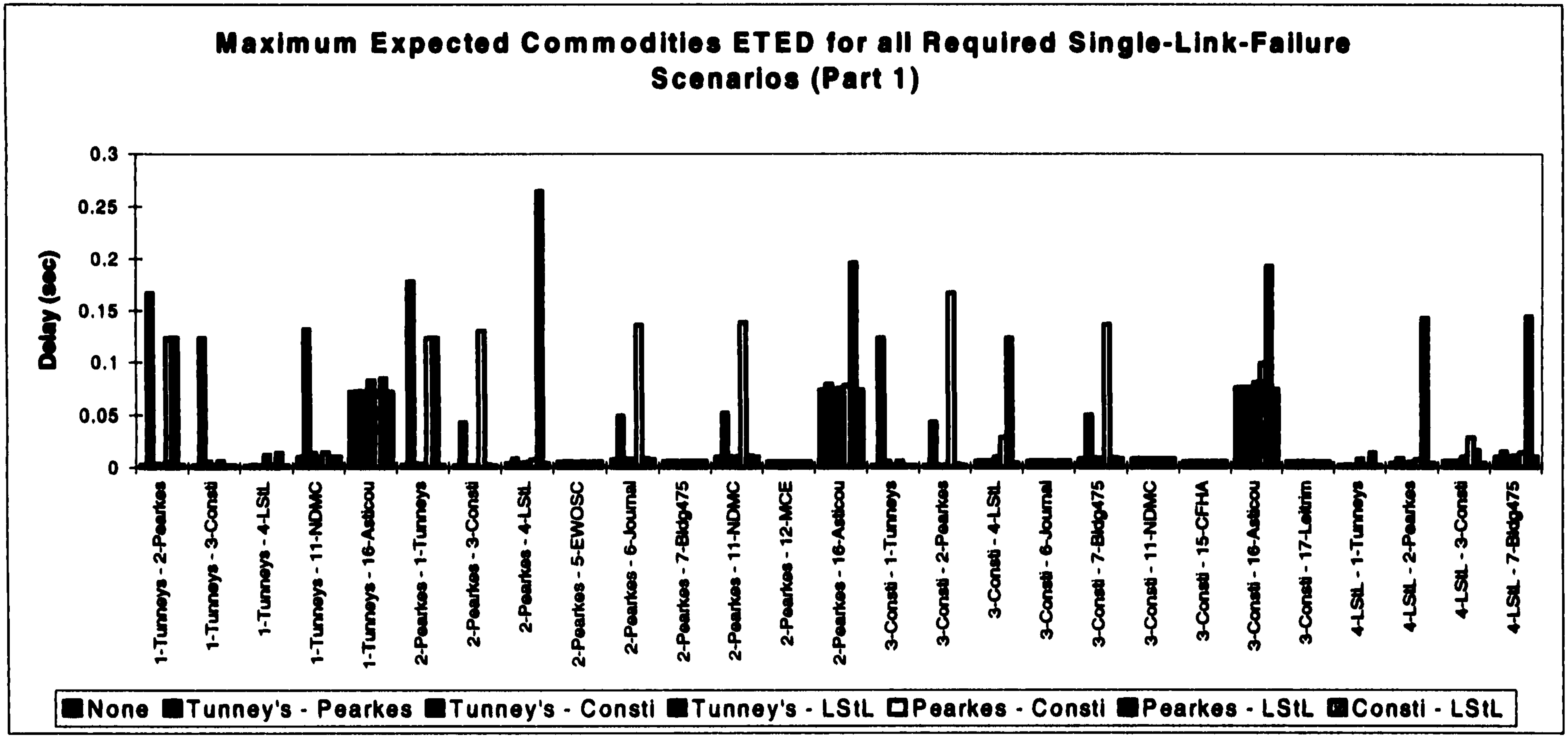
```
    -(<)--Demand Pair----Flow(Bps)------
      2-Pearkes > 1-Tunneys        4482000
      2-Pearkes > 3-Consti        2300400
      2-Pearkes > 6-Journal        900
      2-Pearkes > 11-NDMC        97200
      7-Bldg475 > 3-Consti        900

 * Network State = 5 => Link "2-Pearkes - 4-LStL" has failed.
    -Total Flow(Bps)---Utilisation(%)---Expected Delay(Sec)-
        7660405             99.228            0.123500293648817

    -(>)--Demand Pair----Flow(Bps)------
      1-Tunneys > 2-Pearkes        414000
      4-LStL > 2-Pearkes        2321010
      4-LStL > 7-Bldg475        14400
      16-Asticou > 2-Pearkes        348300

    -(<)--Demand Pair----Flow(Bps)------
      2-Pearkes > 1-Tunneys        4482000
      2-Pearkes > 4-LStL        80695

 * Network State = 6 => Link "3-Consti - 4-LStL" has failed.
    -Total Flow(Bps)---Utilisation(%)---Expected Delay(Sec)-
        4896000             63.4197            0.00260623229461743

    -(>)--Demand Pair----Flow(Bps)------
      1-Tunneys > 2-Pearkes        414000

    -(<)--Demand Pair----Flow(Bps)------
      2-Pearkes > 1-Tunneys        4482000


==================================
Link: 1-Tunneys - 3-Consti
==================================

Etc. for all links of the network solution
```

```
************************************
**       Nodes INFORMATION        **
************************************
==================================
Node: 1-Tunneys
==================================
Capacity (pps): 100000
 * Network State = 0 => no link failure.
    Total Load (pps): 181
    Utilisation (%): 0.181
    Expected Delay (sec): 1.0018132820408E-5

 * Network State = 1 => Link "1-Tunneys - 2-Pearkes" has failed.
    Total Load (pps): 181
    Utilisation (%): 0.181
    Expected Delay (sec): 1.0018132820408E-5

 * Network State = 2 => Link "1-Tunneys - 3-Consti" has failed.
    Total Load (pps): 181
    Utilisation (%): 0.181
    Expected Delay (sec): 1.0018132820408E-5

 * Network State = 3 => Link "1-Tunneys - 4-LStL" has failed.
    Total Load (pps): 181
    Utilisation (%): 0.181
    Expected Delay (sec): 1.0018132820408E-5

 * Network State = 4 => Link "2-Pearkes - 3-Consti" has failed.
    Total Load (pps): 557
    Utilisation (%): 0.557
    Expected Delay (sec): 1.00560119867671E-5

 * Network State = 5 => Link "2-Pearkes - 4-LStL" has failed.
    Total Load (pps): 609
    Utilisation (%): 0.609
    Expected Delay (sec): 1.00612731535055E-5

 * Network State = 6 => Link "3-Consti - 4-LStL" has failed.
    Total Load (pps): 227
    Utilisation (%): 0.227
    Expected Delay (sec): 1.00227516462437E-5


==================================
Node: 2-Pearkes
==================================

Etc. for all nodes of the network
```

```
*************************************
**     COMMODITIES INFORMATION     **
*************************************
==================================
Commodity: 2-Pearkes - 4-LStL
==================================
Total traffic demand:  1112400 Bps
 * Network State = 0 => no link failure.
    Expected End to End Delay: 0.00394876537044553 Sec

    Direction        Link ID           Flow       Expected Delay(Sec)
        >        2-Pearkes-4-LStL        1112400          0.00392365923872262

 * Network State = 1 => Link "1-Tunneys - 2-Pearkes" has failed.
    Expected End to End Delay: 0.00908463429328776 Sec

    Direction        Link ID           Flow       Expected Delay(Sec)
        >        2-Pearkes-4-LStL        1112400          0.00905952080550776

 * Network State = 2 => Link "1-Tunneys - 3-Consti" has failed.
    Expected End to End Delay: 0.00394877054663567 Sec

    Direction        Link ID           Flow       Expected Delay(Sec)
        >        2-Pearkes-4-LStL        1112400          0.00392365923872262

 * Network State = 3 => Link "1-Tunneys - 4-LStL" has failed.
    Expected End to End Delay: 0.0052698895715082 Sec

    Direction        Link ID           Flow       Expected Delay(Sec)
        >        2-Pearkes-4-LStL        1112400          0.00524478016104979

 * Network State = 4 => Link "2-Pearkes - 3-Consti" has failed.
    Expected End to End Delay: 0.00800513827925897 Sec

    Direction        Link ID           Flow       Expected Delay(Sec)
        >        2-Pearkes-4-LStL        1112400          0.00798000661386311

 * Network State = 5 => Link "2-Pearkes - 4-LStL" has failed.
    Expected End to End Delay: 0.264570340550563 Sec

    Direction        Link ID           Flow       Expected Delay(Sec)
        <        1-Tunneys-2-Pearkes       80695          0.123500293648817
        >        1-Tunneys-4-LStL        80695        0.014525216842145
        >        2-Pearkes-3-Consti        1031705          0.0029842213351543
        >        3-Consti-4-LStL       1031705        0.123500293648817

 * Network State = 6 => Link "3-Consti - 4-LStL" has failed.
    Expected End to End Delay: 0.00394876767985863 Sec

    Direction        Link ID           Flow       Expected Delay(Sec)
        >        2-Pearkes-4-LStL        1112400          0.00392365923872262


==================================
Commodity: 2-Pearkes - 5-EWOSC
==================================
Etc. for all commodities of the network solution
```

Appendix F

Expected ETED for each commodities



Maximum Expected Commodities ETED for all Required Single-Link-Failure Scenarios (Part 1)

Maximum Expected Commodities ETED for all Required Single-Link-Failure Scenarios (Part 2)