ACTA
FORESTALIA
FENNICA
227

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PLANNING A FOREST ROAD NETWORK BY A SPATIAL DATA HANDLING-NETWORK ROUTING SYSTEM

METSÄTIEVERKON SUUNNITTELU SIJAINTITIETOKANTAMENETELMÄLLÄ

PLANNING A FOREST ROAD NETWORK BY A SPATIAL DATA HANDLING-NETWORK ROUTING SYSTEM

Metsätieverkon suunnittelu
sijaintitietokantamenetelmällä

Jimin Tan

The basic objective in planning a forest road network is to minimise the total cost of terrain transportation, road transportation, road construction and maintenance by controlling the road location, road network density and road quality, besides environmental and ecological considerations. Studies on the optimisation of forest road network have encountered difficulties in taking into account the spatial diversity of forest terrain and stands. The spatial data handling-network routing system developed in this study proves to be useful in assisting forest managers to carry out the planning of forest road networks by covering the spatial and economic analyses. The system applies the techniques used in geographic information systems (GIS) in the manipulation of the necessary spatial data. The system uses shortest path algorithms for analysing terrain transportation, road transportation and road construction in a given planning area. A greedy-heuristic algorithm was developed to automate the locating of roads. Using the alternative locations of a forest road network, the system calculates many values such as terrain transportation distance, terrain transportation cost, road transportation cost, road extending length, and the cost of constructing a new road, which are useful in carrying out of sensitivity analyses. The system is also applicable as an aid in the selection of forest road standards. Bounded road catchment area and limited road extending reach were used in road locating by the greedy-heuristic algorithm to achieve better road locating results. A local network routing model was developed for improving the capacity of the system.

Metsätieverkon suunnittelussa on perustavoitteena minimoida metsäkuljetuksen ja metsätienrakennuksen kokonaiskustannukset mitoittamalla tieverkon tiheys, teiden sijainti ja laatu asianmukaisesti ja kiinnittämällä lisäksi huomiota ympäristönsuojeluun ja ekologiaan liittyviin näkökohtiin. Maaston ja puuston paikallisen vaihtelun ottaminen huomioon muodostaa ongelman metsätieverkon optimointitutkimuksissa. Tässä tutkimuksessa kehitetty sijaintitietokantaa hyväksi käyttävä tieverkon suunnittelujärjestelmä osoittautui käyttökelpoiseksi menetelmäksi, mikä auttaa metsätalouden suunnittelupäätöksiä tekeviä henkilöitä tien sijaintia ja rakentamisen taloudellisuutta koskevissa analyyseissä. Menetelmässä sovelletaan paikkatietojärjestelmän (GIS) tekniikkaa tarpeellisen sijaintitietokannan käsittelyssä. Se käyttää valitun alueen puitteissa lyhimmän polun mallia maasto- ja tiekuljetuksen sekä tienrakennuksen analysoinnissa. Menetelmään sisältyy algoritmi tien paikan automaattista sijoittamista varten. Vaihtoehtoisten metsätieverkon sijaintien mukaan menetelmä laskee monia sellaisia maasto- ja tiekuljetuksen, tien pidentämisen tai uuden tien rakentamisen kustannusarvoja, joita voidaan käyttää hyväksi herkkyysanalyysissä. Menetelmää voidaan myös käyttää hyväksi tieluokan valinnassa. Tutkimus osoittaa, että asianmukainen metsätien vaikutusalueen rajaaminen ja tien jatkaminen vain rajallisesti parantavat suunnittelutulosta ja teiden sijoittamista ja tästä syystä onkin kehitetty menettelytavan parantamiseksi lähitieverkon suunnittelumalli.

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List of main symbols

Symbols for sets (boldface)

B = set of branching road nodes

$\mathbf{D_8}$ = set of direction codes containing numbers from 1 to 8 that correspondingly represent east, north-east, north, north-west, west, south-west, south and south-east

$\mathbf{E_i}$ = set of neighbouring nodes of node i

M = set of all nodes in a neighbourhood region

N = set of all nodes in the planning area

O = set of entry (or exit) nodes

R = set of road nodes

S = set of positive land nodes for road construction

T = set of nodes with temporary labels

Symbols for matrices (bold italic)

BS = (bs_i) is an array, where $bs_i \in \mathbf{B}$ is called the nearest branching road node to node i such that the cost of road construction is the lowest between bs_i and the positive land node $i \in \mathbf{S}$

C = (c_{ij}) is a cost matrix, where c_{ij} is the minimum cost, distance or the like, from node i to j, $i \in \mathbf{N}$, $j \in \mathbf{N}$

CH = (ch_{ij}) is the cost matrix for road transportation, where ch_{ij} is the minimum cost of road transportation between node i and j, $i \in \mathbf{R}$, $j \in \mathbf{R}$

CO = (co_i) is an array of the road transportation costs outside the planning area, where co_i is the cost of the road transportation outside the planning area and bordering the planning area at node $i \in \mathbf{O}$

CR = (cr_{ij}) is the cost matrix for forest road construction and maintenance, where cr_{ij} is the minimum cost of the road construction and maintenance between node i and j, $i \in \mathbf{N}$, $j \in \mathbf{N}$

CS = (cs_{ij}) is the cost matrix for terrain transportation, where cs_{ij} is the minimum cost of terrain transportation between node i and j, $i \in \mathbf{N}$, $j \in \mathbf{N}$

CT = (ct_i) is an array of the total transportation cost for each node $i \in \mathbf{N}$, where ct_i is the cheapest total cost combining all forms of transportation for node i

H = (h_{iJ}) is the matrix for conversion between the regional labels and area labels, where h_{iJ} = the area node label for a given regional node J in the neighbourhood region of node i if it exists; otherwise $h_{iJ} = 0$, $i \in \mathbf{N}$, $J \in \mathbf{M}$

L = (l_{ij}) is a link length matrix, where l_{ij} = length of the link (i, j), for all $j \in \mathbf{E_i}$; $l_{ii} = 0$; otherwise $l_{ij} = \infty$, $i \in \mathbf{N}$, $j \in \mathbf{N}$

OT = (ot_i) is an array, where ot_i is called a nearest entry node to node i, and ot_i is at the boundary of the planning area, $i \in \mathbf{N}$, $ot_i \in \mathbf{O}$

P = (p_{ij}) is a path matrix, where p_{ij} is the node preceding j on the shortest path from node i to j, $p_{ij} \in \mathbf{N}$, $i \in \mathbf{N}$, $j \in \mathbf{N}$

PH = (ph_{ij}) is the path matrix for road transportation, where ph_{ij} is the node preceding node j on the shortest path from node i to node j, $i \in \mathbf{R}$, $j \in \mathbf{R}$

PR = (pr_{ij}) is the path matrix for forest road construction and maintenance, where pr_{ij} is the node preceding j on the shortest path from node i to j, $i \in \mathbf{N}$, $j \in \mathbf{N}$

PS = (ps_{ij}) is the path matrix for terrain transportation, where ps_{ij} is the node preceding j on the shortest path from node i to j, $i \in \mathbf{N}$, $j \in \mathbf{N}$

PT = $[\mathbf{\textit{RT}, \textit{OT}}]$ is the path array for combined transportation (including terrain transportation and road transportation), and the combined forest transportation is assumed to take place in the cheapest way along route $i \rightarrow rt_i \rightarrow ot_i$, where $i \in \mathbf{N}$, $rt_i \in \mathbf{R}$, $ot_i \in \mathbf{O}$

RT = (rt_i) is an array, where rt_i is called a nearest road node to node i, at which transportation mode changes between terrain transportation and road transportation, $i \in \mathbf{N}$, $rt_i \in \mathbf{R}$

Z = (z_i) is an array of the link node attributes, in terms of cost, distance or the like, where z_i is the attribute value for node i, which is needed to determine the link attribute, $i \in \mathbf{N}$

Other symbols

β = radius of bounded road catchment area

C_{er} = total cost of extended road

DINFO = procedure for data input and network formulating operations

d_r = road network density

D_s = average terrain transportation distance

FIM = Finnish mark

FRNET = procedure containing forest road network extending tools

GCT = grand total of transportation cost for the entire area

GIS = geographic information system

l = grid cell size

L_{er} = total length of extended road

μ = ratio of marginal benefit to marginal cost

M_{br} = radius of neighbourhood region in number of grid cells

m_{br} = radius of neighbourhood region using map distance

n = total number of nodes in the network of the whole planning area

n_m = total number of nodes in neighbourhood region network

OR = operations research

π = net benefit

P_F = significance probability

ρ = limited road extending reach

R^2 = coefficient of determination

SPMD = procedure for determining shortest path matrices

S_r = road spacing

Preface

This study was carried out at the Department of Forest Resource Management, University of Helsinki. I would like to express my sincerest thanks to my supervisor Prof. Rihko Haarlaa, who has provided guidance, comments and assistance from the very beginning to the completion of the study, and who also helped me in translating the Finnish text. Prof. Matti Keltikangas originally proposed this research topic. I am deeply indebted to him for his support, suggestions and criticism. I would also like to express my appreciation to Dr. Martti Saarilahti, whose encouragement and interesting discussions with me in the beginning of this research project have been very helpful.

I would like to thank Prof. Kalle Putkisto, Prof. Matti Kärkkäinen, Prof. Esko Mikkonen, and Mr. Arto Rummukainen, L.Sc. (For.), who have read the manuscript and made valuable comments and discussions. Professor Mikkonen read the final manuscript again and made several discerning comments and corrections concerning it. I wish to extend my gratitude to Hannu Niemelä and Ilpo Greis from Central Forestry Board TAPIO; Ukko Holopainen, Tapio Tyynys and Jorma Holopainen from Ylikemin hoitoalue, National Board of Forestry, with whom I had discussions on the first hand material and expertise knowledge.

I wish to express my sincere gratitude to the Foundation for Research of Natural Resources in Finland, the Department of Forest Resource Management of the University of Helsinki, and the Nordic Council on Forest Operations (NSR), who financed this research project. The support of the staff at the Department of Forest Resource Management is greatly appreciated. I am grateful to the Chinese and Finnish governments, who gave the opportunity for me to study in Finland and provided finance for the earlier studies, which have been of great importance to the current work.

During the final correction of the manuscript, Prof. Pertti Harstela and Prof. Ari P.J. Vepsäläinen provided me very useful comments in reviewing my thesis. Prof. Vepsäläinen has read many versions of my manuscript and provided important criticism and help. I also received finance from the Niemi Foundation and University of Helsinki. Mr. Erkki Pekkinen corrected the English text. I gratefully acknowledge their assistance. Finally, I would like to thank my wife Guilan Wu for her assistance, encouragement and understanding during the many years spent on this study.

Helsinki, July, 1992
Jimin Tan

1 Introduction

1.1 Problem of forest road network planning

A forest road network provides easy access to forests and facilitates activities for the development, protection and use of forest resources, here referred to as forest-related activities (Carder and Mandt 1971). The movement of labour, products, materials, tools and so on, is usually difficult in forest terrain. Forest roads are constructed to achieve easier and cheaper transportation.

For the development of forest industries and intensive forest management, sufficient forest roads are very essential. To take an example, the total length of permanent forest roads built annually in Finland have increased from about 300 km at the beginning of 1950's to over 3 000 km by the year of 1988 (Uusitalo 1989). Today, the forested areas of southern and northern Finland have a forest road spacing between 350 m and 700 m respectively. According to the 2000-forest program, about 40 000 km of permanent forest roads are still needed (Antola 1991). In addition to an increase in the road network density, the requirements on forest road quality have also risen. As timber transportation methods have gradually changed from the use of horses to heavy mechanised vehicles, the trend of massive use on temporary winter roads has shifted towards the use on higher quality and more year-around forest roads (Hakkila 1989).

The increase in the amount and quality of forest roads is based on the needs to reduce timber transportation costs. However, the heavy investment and maintenance costs involved call for better planning of forest road networks. The average cost of road construction in Finland has recently been about FIM 40 000/km (Uusitalo 1989). The total cost of a forest road, as an investment on forest land, accounts for about 24 per cent of the total costs of silviculture and forest improvement work, of which the costs of new road construction, old road maintenance and road planning account for about 17 %, 5 %, and 2 % correspondingly (Uusitalo 1989). It should not be ignored that inappropriate road construction can lead to financial loss since any mistakes that are made are irreversible and permanent.

Forest managers are concerned with how forest-related activities can be conducted in the most economical way by planning an appropriate forest road network that takes into consideration both timber transportation and road construction, as well as their environmental impacts. Sundberg and Silversides (1988) considered forest roads as being systems of lines serving forest areas in two functions: a longitudinal (lengthwise) function to support the timber transportation carried out on the roads; and a lateral (crosswise) function to connect off-road forest transportation. To fulfil the longitudinal function, forest roads are built to meet certain standards. Forest roads of high standard support easier transportation, and hence bring about lower transportation cost, but higher road standards also mean higher road costs. When roads are built to meet the minimum requirement for performing the longitudinal function, the standard of the roads has no impact on the roads' lateral function. With regard to the lateral function, forest roads serve as points of collection or distribution to areas, or as the points where the transportation mode changes. More forest roads mean shorter off-road transportation distances, and thus lower off-road transportation costs, but more roads also mean greater investment and maintenance costs. Furthermore, different locations for a particular forest road may result in different road costs due to terrain restrictions. A different road location may lead to a difference in the value of the average off-road transportation distance (von Segebaden 1964), and hence different off-road transportation costs. By taking both longitudinal and lateral functions of forest roads into account in planning a forest road network, the forest managers can minimise the total cost of terrain transportation, road transportation, road construction and maintenance by manipulating the road network density, road location and road standard in a desired way.

The growing need to control the costs of

forest operations motivates forest managers to develop efficient methods for planning forest road networks so as to minimise the total cost of terrain transportation, road transportation, road construction and maintenance. Due to the difficulty brought about by the complexity and variability of the forest environment, the planning of forest road networks is usually carried out by experienced personnel using non-optimising rules of thumb. Mathematical models on the optimisation of forest road network have limitations with regard to being able to take into account the diversity of forest terrain and stands, which substantially influence the determining of road network density, road location and road standards. The techniques of geographic information systems and operations research have proved to be promising in solving the problem of forest road network planning (Turner and Miles 1971, Morofsky 1977, Nieuwenhuis 1986, Kobayashi and Nitami 1992).

1.2 Objective and scope

The purpose of this study is to develop and demonstrate a method to assist forest managers in planning forest road networks. This method is designed to enable forest managers to do the spatial and economic analyses and to determine the desired road network density, road location, and road standard with the objective of minimising the total cost of terrain transportation, road transportation, road construction and maintenance.

Forest road network planning in this study focuses on internal forest roads. Internal forest roads are located within a forest area and they serve mainly forest-related activities. The case study of this dissertation is limited to forest operations (i.e. forest stand establishment, stand improvement, stand protection, and logging). The use of forest roads for other purposes (e.g. recreation, agriculture, public transportation) is not included; these can be taken into account if their effects on the forest road network are converted into costs and benefits.

Road locating here is limited to only one quality of forest roads because the changes in forest road standards do not influence the determination of forest road location (Sund-

berg and Silversides 1988). Normally road locating starts with a lowest road standard. Selection of a road with a higher standard can be evaluated after the road locations have been determined. The change-over from temporary winter roads to permanent roads cannot be evaluated since the techniques used in building temporary winter roads are different from those used in building year-around forest roads, and hence the cost structure is different. For this reason, the road locating is limited to year-around forest roads.

Timber transportation is limited to two types: off-road (or terrain) transportation, and long-distance transportation. The given forest area should be independent so that terrain transportation within the forest road planning area should not influence, and is not influenced by, that of the surrounding forest areas. The links of terrain transportation with the long distance transportation system are assumed to have been determined in advance. Long-distance transportation mainly includes forest transportation by road. Transportation by waterway or on railway also can be included as a fixed transportation route as is the case with an existing road. Entrances to the given forest area are determined beforehand. The markets, mills, labour resources, material resources are assumed to be known, and their connections with the planning area are given and taken into account at the boundary of the planning area.

The terms of cost and benefit are used to evaluate the terrain transportation, road transportation, road construction and maintenance. All the costs and benefits in the case study were estimated using 1988 figures. This report does not include the study on data collection, which may come from many sources, such as forest management documents, literature, expertise knowledge, reconnaissance in the field and so on. Landing spacing and road end turning places are not included in the cost-benefit analysis. Forest road design and field road construction are not dealt with in this study.

1.3 Study outline

Studies on the optimisation of forest road networks have been conducted over many

decades. Chapter 2 reviews the relevant literature on conventional road network planning and automated road locating, and on the application of geographic information systems (GIS) and operations research (OR) principles. GIS and OR techniques were found to be useful, but neither GIS nor OR have been developed for the express purpose of planning forest road networks. Therefore a simple system called a spatial data handling-network routing system was developed in the course of this study by adapting GIS and OR techniques. A brief overview of the spatial data handling-network routing system is given in the beginning of chapter 3. This is followed by presenting the principles used in developing the system.

Chapter 4 demonstrates the application and adaptation of the spatial data handling-network routing system with an empirical example. The system is first applied to the example to obtain an approximate to the optimum solution of the road network location. Different solutions are then arrived at through road locating modifications. The solutions are then compared and discussed. The method of road standard selection is further adapted to the conditions in the case study. Road locating is further investigated by observing the road network extending process and by carrying out the sensitivity analysis of road network density and benefit over cost elements.

Finally, chapter 5 presents the summary and conclusions of the research, and discusses the capabilities, limitations, and possible further development of the spatial data handling-network routing system.

2 Review of related literature

2.1 General

This chapter is a review of two aspects of the literature related to forest road network planning: conventional road network planning and automated road locating. In conventional road network planning, general information is given about the road factors, road types, road spacing models and road routing procedures. Automated road locating consists of two primary procedures: network formulating and road locating, where geographic information systems (GIS) and operations research (OR) are found to be applicable. Consequently, the relevant GIS and OR techniques are presented and discussed as to their usefulness in the planning of forest road networks.

2.2 Conventional forest road network planning

Forest road network planning usually deals with the determination of road network density, road location and road quality with the objective of minimising the total cost of terrain transportation, road transportation, road construction and maintenance. When a

project on planning a forest road network is given, there are a variety of factors to be considered. The main factors may be categorised as follows (Allal and Edmonds 1977, Minamikata 1984, Kantola and Harstela 1988):

— *activities* to be conducted in the forests, including mainly forest-related activities;
— *technologies* used in conducting these forest-related activities;
— *forests* to be accessed, including forest stand, volume, species etc. and their spatial locations;
— *environment*; e.g. terrain, soil, weather;
— *forest roads* as a network for accessing the forests, concerning their construction and maintenance;
— *non-forestry use* of forest roads (e.g. agricultural, public);
— *other constraints* (e.g. ownership, government policies and regulations).

It is a complex and difficult task to include all the above factors into a road planning project. Commonly, the influences of these factors are interpreted into quantitative values in terms of costs and benefits so that the break-even relations in determining the road quality, road network density and road location can be found. Some factors are

difficult to evaluate quantitatively. They are usually rated with great care, and by individuals possessing expertise in various fields. The costs and benefits are estimated on the basis of available information, including expert knowledge, literature data, forest inventory documents, forest management planning documents, topographic maps, forest maps, aerial photos, field reconnaissance, etc.

Road quality is normally classified using different categories — i.e. road standards. Road standards are defined by factors such as bearing capacity, desired speed, minimum sight distance, minimum radius of curvature, maximum gradient and maximum length of grade, road width, traffic density and expected life (Pulkki 1980). The following international forest road classes are found from the literature (FAO 1977):

1) Haul roads:
   — primary or main roads;
   — secondary roads;
   — feeder roads.
2) Skidding or forwarding trails.
3) Access roads.

Frequently, forest road planning is concerned with haul roads while the skidding or forwarding trails (they do not require formal construction) and access roads (they are purely functional and do not imply any standard or quality of road) are not included.

In Finland, there are three forest road categories (Metsäteiden rakentamista... 1988, Antola 1991):

1) Main forest roads.
2) Area forest roads.
3) Branch forest roads.

Pulkki (1980) compared the standards of forest roads used in Finland with international forest road standards, and stated that the international category of main forest road is not found in Finland. The Finnish main forest road corresponds to the secondary forest road in international classifications, the area forest road corresponds to the feeder forest road and the branch forest road refers to a low standard feeder forest road. A forest road standard can be selected before

D_s - Average terrain transportation distance

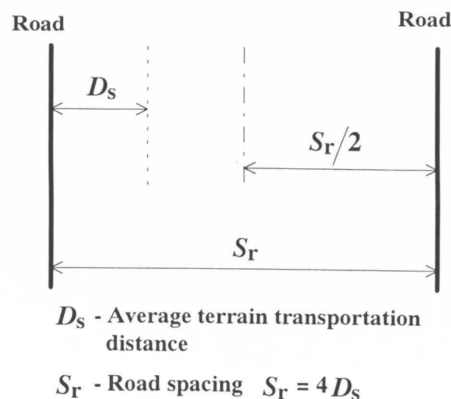S_r - Road spacing $\quad S_r = 4 D_s$

Fig. 1. Road spacing and terrain transportation distance.

or after the road network has been located or while planning is in progress.

As stated earlier, the quality of a forest road is a factor affecting on both road cost and transportation cost. Generally higher road quality requires higher investment but reduces the cost of timber transportation. Porpaczy and Waelti (1976) stated that the determination of forest road quality is simply one of finding the least-cost solution (Matthews 1942, Sundberg and Silversides 1988).

One of the important factors in the process of planning a forest road network is that of optimum road spacing. Peters (1978) stated that optimum road spacing has been used as a starting point in the planning of timber harvesting in undeveloped areas (FAO 1974, Rowan 1976) and when extending existing road networks (Minamikata 1977) and when evaluating the efficiency of current operations (Peyton 1973). Road spacing assumes a twofold role in the analysis of forest road systems. Firstly, it is a reflection of the off-road transportation distance which in turn influences the cost of off-road transportation. There is a directly proportional relationship between off-road transportation distance and road spacing (Fig. 1). Secondly, it is a reflection of road network density which directly influences the cost of road construction and maintenance. Road network density is defined as the length of road built per unit area, which has a
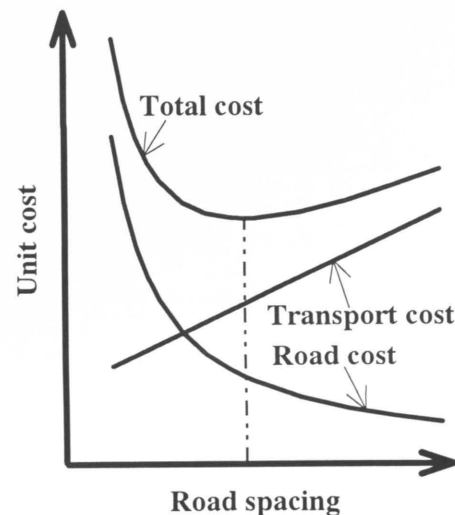

Fig. 2. Road spacing costing.

reverse proportional relationship to road spacing (von Segebaden 1964): $d_r = k/S_r$, where S_r — road spacing, k — a constant, d_r — road network density. Briefly, if road spacing decreases, the cost of off-road transportation is reduced, but the cost of road construction and maintenance is increased, and vice versa. The optimum road spacing is that which minimises the total cost of timber transportation and road construction (Fig. 2).

Earlier studies on determining forest road spacing can be founded in literature; e.g. Klemencic (1939), Matthews (1942). Putkisto (1956) have presented several models derived by calculus for calculating average terrain transportation distances with different tree felling directions and different log collecting methods. Larsson (1959) also used calculus to solve this problem and his method was later used by Larsson and Rydstern in 1968. Varied forms and applications of these models have been used by many authors. Suddarth and Herrick (1964) refined the method for calculating the average skidding distance as a general model. It was further developed by others; e.g. Lysons and Mann (1965) for circular settings, Peters and Burke (1972) and Twito and Mann (1979) who used programmable calculators. The spacing of landings and roads, as well as their combinations, were improved by

Peters (1978), Bryer (1983), and were solved also by means of microcomputer applications (Holman et al. 1976, Sessions and Li 1987). Minamikata (1977) developed a model of spur road network density increment for two different road classes. These mathematical models defined optimum road spacing to minimise the total cost of timber transportation and road construction. Thompson (1988) determined the optimum spur road spacing at which profit was maximised by taking the marketing price into account.

Common assumptions made in road spacing studies are that roads are parallel, equidistant and straight; and that the topography and soil conditions are uniform from the standpoint of production costs, operating costs, and road costs (Larsson 1959). These assumptions do not hold in most cases of practical applications. A forest road network can have as much diversity as the terrain itself (Sedlak 1981). The optimum road spacing defined by the above mentioned studies can be used only as a general guide as is supposed by these models when determining the location of forest roads, but they do not provide any position as to where a forest road should be located.

Locating a route for a forest road is mainly determined by economic considerations and by the topography of the area which the road must cross. Different routes may yield different road-induced benefits and different road construction costs, road maintenance costs, and road user's costs. Extreme terrain conditions, such as valleys, water, peatlands, steep slopes, and big rocks, restrict the routing of roads (Allal and Edmonds 1977).

Road-induced benefits are usually interpreted as the amount by which costs are reduced when building the road, and this cost is calculated within the road catchment area. Generally, the road catchment area is the area around the road within which all road transportation is performed on the particular road. The road catchment area is sometimes called a road influenced area (von Segebaden 1964) or a road drainage area (Sundberg and Silversides 1988).

The general planning for forest road locations may be seen to consist of three steps (Allal and Edmonds 1977, FAO 1977, Hogan 1973):

1) To find alternative routes or route nets, which are feasible both technically and economically. For a given road planning area, there may exist more than one possibility for the location of a forest road or road network. When, at times, the possibilities are too large or even endless, a reasonable number of highly feasible alternatives must be found. The preparation of background materials, such as cost data, is a prerequisite of this planning process.

2) To evaluate all the feasible alternative routes or route nets. An economical (e.g. cost-benefit) analysis must be made of each alternative found during the first stage.

3) To select the best and thus attain the minimum cost or maximum benefit.

Forest road design and construction are also part of road planning but these are not included in this study. For further information on forest road design and construction, the reader is referred to the relevant literature: an example of general instructions concerning with forest road construction techniques is the work by Antola (1988); and examples of studies on using computer assisted design in forest road construction are those by Hogan (1973), Abeli (1985), Dürrstein (1987).

Computers can be used to assist in the calculations necessary in these planning processes. In the Ylikemi forest district, for example, of the Finnish National Board of Forestry, a spreadsheet programming system is used for this type of calculations. In this system, feasible alternative routes are found by experienced road planning personnel who are guided by rules of thumb such as optimum road spacing. The spreadsheet program assists in the calculations necessary in performing cost-benefit analysis for a given feasible road route. However, some important aspects are not included in this system: the computer programs are not designed to provide the spatial positions where the forest roads should be located; the system does not determine how much road is needed; neither is there provision for spatial analysis or sensitivity analysis. Thus, it is of great importance for this study to develop a system that automates road locating, determines optimum road network density and facilitates the selection of desired road standards, and all this with the objective of minimising the total cost of terrain trans-portation, road transportation, road construction and maintenance.

2.3 Automated forest road locating

The typical procedure of automated forest road locating generally includes two primary steps: network formulating and road locating.

1) Network formulating

Network formulating is concerned with determining the nodes and links contained in the network. Hogan (1973) defined the links as physical segments in the transportation system identified by type of facility, travel speed, width, surface type, jurisdiction, or costs of road or transportation etc. Links may be existing roads, roads to be constructed, or other modes of transportation. Nodes are connected by links and they are the points through which the resources of a management unit must pass for transportation to markets, or points through which people must pass to use a camping ground or wilderness area. In networks, nodes are generally points at which decisions are made and links are actions.

The formulation of the network must be performed with care so as to include all feasible routes. There are two ways to formulate a network: systematically or empirically.

a) Systematical formulation

Systematical formulation of a network is based on certain rules; e.g. to use a grid system (Morofsky 1977, Kobayashi 1984, Minamikata 1984, Nieuwenhuis 1986, Douglas and Henderson 1987) or to follow contour lines (Sakai 1984). The advantages of these methods are that it is simple in manipulation and it does not require an empirical predefining of the network elements. The disadvantages of the method are that it includes numerous nodes and links, and these call for a high level of computer resources.

b) Empirical formulation

In the empirical formulation of a network, road planning specialists define the nodes and links of the network. Examples of this method are those used by Hogan (1973), Wijngaard and Reinders (1985), Session (1985), Thieme (1987). The advantages of using this method are that some obviously infeasible nodes and links such as those passing through non-land areas are excluded. Thus, less computation is needed in evaluating the alternatives of a road route since fewer nodes and links are included in the network in comparison with systematic formulation, but the empirical approach requires high personnel expertise. Otherwise the structure of road network may not be economically complete, and several better routes may be missing due to errors in the formulation of the network.

The formulation of the network may be much easier if some spatial data handling system is available; e.g. geographic information systems (GIS) or digital terrain model (DTM) (Twito et al. 1987b). Therefore, another aspect of this study is the development of a simple spatial data handling system by applying GIS techniques.

2) Road locating

Road locating is concerned with finding the most appropriate route for a road or road network. For locating a road between a pair of points (origin-destination), heuristic algorithms (Morofsky 1977, Pulkki 1984), and the shortest path algorithms (e.g. Turner and Miles 1971, Minamikata 1984) can be applied in determining the road route of the least cost; while the dynamic programming by Douglas and Henderson (1987) can locate the road route with the greatest benefit. The Travelling Salesman Algorithm (Wijngaard and Reinders 1985) and minimum spanning tree model (Dykstra 1984) are useful for finding a road network connecting a certain number of points (e.g. centres of forest areas or compartments) with the minimum cost of road construction. These algorithms require some expert instructions to enable these points to be connected by the road network.

When locating internal forest roads, it is common that the points to be connected are unknown except for the given starting points. In such a case, it is difficult to locate a forest road that would minimise the total cost of terrain transportation, road transportation, road construction and maintenance. Some algorithms are reported in the literature (e.g. Kobayashi 1984, Nieuwenhuis 1986) for estimating the optimum solution when locating internal forest roads. The road locating method presented by Kobayashi (1984) uses a heuristic rule that begins with a given starting point, and moves iteratively to a neighbouring node to achieve the greatest benefit to cost ratio at each iteration, until a satisfactory road system is found. In this method, the routes between non-neighbouring nodes are not found before road locating, then it is difficult to cross over extreme terrain. Nieuwenhuis (1986) defines the routes for road construction between any pair of the nodes by the least cost paths, and then finds the alternative road routes to be equally spaced by using the rule of maximum ratio of cell coverage to cost. Timber transportation and forest stands are not considered, and thus the cost-benefit analysis and spatial analysis concerning the road locations are limited. It is very important for this study to provide an improvement to the way that cost-benefit analysis and spatial analysis are performed.

2.4 Application of geographic information systems

Spatial information is indispensable in planning forest road networks. Virtually, maps, which are important tools for storing and conveying spatial information, are necessary when a project concerning planning a forest road network is initiated. Traditionally, forest managers have relied on spatial information in the form of hand-compiled maps (e.g. topographic maps, forest cover-type maps) when planning forest road networks. The consideration of spatial variation of terrain, forest stands, etc., requires much experience and skills on the part of the personnel. Quantitative approaches to modelling spatial relationships are often limited. The introduction of geographic information systems (GIS) into forest resource manage-

ment enables forest managers to address this complex issue in new ways.

GIS technology has arisen from advances in merging database management systems and mapping (Erdle and Jordan 1984, Cooney and Tucker 1986). Recent GIS developments have augmented its basic functions. Berry (1986) has summarised the basic functions of GIS as computer mapping, spatial data management, spatial statistics, and cartographic modelling.

Geographic information system (GIS), also called Map Based Information System (MBIS), is defined as being a computer-based system for handling geographically referenced data to support decision making processes. It consists of four major components (Marble 1984, Burrough 1986):

1) Data input, which contains all the operations in getting compatible digital form data into a database from existing maps, field observations, remote sensors, etc.; and operations such as data collection, data entry, data updating and data verification.

2) Data storage and database management, which deal with the way how data is stored, structured and organised, and how data is perceived by the users of the system, as well as the necessary transformation and combination of data overlays, where the data overlays are defined as sets of Cartesian arrays representing different geographical attributes.

3) Data manipulation and analysis, which performs a variety of tasks such as changing the form of the data through user-defined aggregation rules or producing estimates of parameters and constraints for various space-time optimisation or simulation models.

4) Data output, which is concerned with how data is displayed and how the results of analysis are reported to users. Data may be presented as maps, tables, and figures (graphs and charts) in a variety of ways through hardware such as printers, plotters, visual display units (VDU), magnetic media, etc.

To be a qualified GIS, a software system must include all four of the above stated functions; furthermore, it must perform efficiently in all of the above four areas (Marble 1984).

Geographical data are referenced to locations on the earth's surface by using a standard coordinate system. Burrough (1986) stated that a coordinate system may be a local one, as in the case of a study covering a limited area; or it may encompass a national grid or an internationally accepted projection such as the Universal Transverse Mercator Coordinate System (UTM). The local one is called a relative coordinate system; the national or international one is called an absolute coordinate system.

Burrough (1986) stated that all geographical data can be reduced into three basic topological concepts — the *point*, the *line*, and the *area*. There are two fundamental ways of representing the topological data in digital form: raster and vector, and these may be summarised as follows (Fig. 3) (Burrough 1986, Tomlin 1990).

Raster data structures represent a set of cells located by coordinates; each cell is independently addressed with the value of an attribute. The simplest data structures consist of an array of grid cells (sometimes termed pixels i.e. element of picture). Each grid cell is referenced by its row and column numbers and it contains a number representing the type or value of the attribute being mapped. A point in raster data structure is represented by a single grid cell defined by three elements: a pair of coordinates (x, y); an area defined by cell size $l \times l$ (where l is the grid cell size); and an attribute of the cell. However, the areas covered by cells need not be presented for every cell if the cells are uniform in size and shape like those in a grid system. Lines and areas can be represented by a set of neighbouring points or rasters which are linked for certain purposes. Raster data structures provide ease of data storage, data manipulation, spatial analysis and simulation. They permit the use of relatively simple computer programs and hence the technology involved is cheap. However, they require large space for storing high resolution data; otherwise losses in accuracy and in detail may occur if they are encoded with grid cells of low resolution.

Vector data structures represent three main geographical entities: points, lines, and areas. Points are similar to cells, except that they do not cover areas. Simple lines, or say line segments, are defined at least by their start point and end point. Polygons are sets of line segments. Areas are sets of interconnected coordinates that can be linked to some given attributes. Areas are usually defined by their boundaries (polygons) and attributes. Vector format attempts to represent shapes and sizes as exactly as possible. It has a compact data structure, and hence provides more efficient use of computer storage. However, such data structures are complex, and they require expensive sophisticated hardware and software. Furthermore, it is difficult to apply vector database in the followings: simulation, spatial analysis and combination of different overlays.

The choice between vector and raster data structures depends on the facility available, the purpose of the application, and the use and type of the data. Generally, vector data is used if exact graphic representation is of foremost importance, whereas raster data is used when a high degree of data manipulation is required. Nevertheless, it is possible to retain the advantages of both types of data structures since conversions from vector to raster or from raster to vector are possible via certain special algorithms (Pavlidis 1982). However, these conversions are complicated

and they are profitable only in case of complex GISs.

Rapid developments are making GIS an increasingly powerful tool in handling spatial data. A number of special issues dealing with the applications of GIS to natural resource management have been published; e.g. Allen and Cooney (1986), Cooney and Tucker (1986), Devine and Field (1986a, b), Smart and Rowland (1986), Consoletti (1986), Fleet (1986), Schwaller and Dealy (1986), Berry (1986), Ripple (1986), PE&RS (1987), GIS/LIS '90... (1990), GIS/LIS '91... (1991). Many microcomputer-based programs have also been made available (Richards and Eiber 1985, Radcliffe 1985, Cooney and Tucker 1986, Tucker 1986, Poso et al. 1990) for spatial analysis, including mapping, image-processing, digital terrain model (DTM), and GIS. Although some of them may not be classified as GIS (e.g. mapping programs), they are considered to be useful spatial data handling tools for certain problems. The combination of OR modelling makes the GIS more powerful and useful; e.g. in network analysis using vector data (Lupien et al. 1987, Ralston and Zhu 1991) and in transportation routing (Lee 1990). Nieuwenhuis (1986) presents a method integrated with GIS for locating forest roads, which uses raster data arrays representing the networks. DTM was used by Thieme (1987) as an user interactive graphics interface.

However, the costs of these systems are considerable due to their complexity (Chock 1990). In addition, a GIS may include excessive information since they are not meant for use in planning forest road networks. Such information is not used entirely or directly for planning forest roads. In any case, an interface software is necessary to filter, interpret and transfer useful information. Therefore, it is important for foresters to keep in mind the necessity of conducting a cost-benefit analysis before using these systems or establishing similar systems (Pulkki 1984).

2.5 Use of operations research techniques

Operations Research (OR) is concerned with the applications of scientific methods and
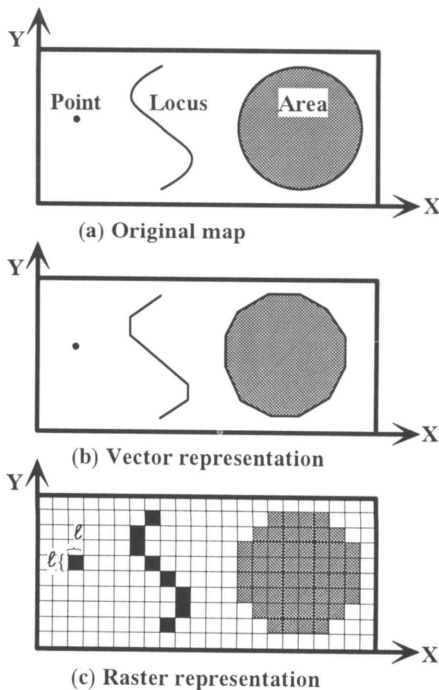
Fig. 3. Digital representations of spatial data.

(a) Original map

(b) Vector representation

(c) Raster representation

techniques to managerial decision-making problems. There are excellent discussions in literature about the use of OR in solving forestry-related problems (e.g. Dykstra 1976, Mikkonen 1983, Dykstra 1984, Pulkki 1984). Forest road network planning implies a problem of network analysis type. The following discussion mainly deals with network models together with some efficient methods of solving network models, including dynamic programming and heuristic programming.

Networks are dealt with by a branch of combinatorial mathematics called graph theory (Ford and Fulkerson 1962, Dykstra 1984). A graph is defined as a collection of nodes and links. A network is a graph for which some quantitative measure is associated with each link. Nodes are simple objects that can have names and other properties, and a link is a connection between two nodes. Other terms used in literature for nodes are vertices, junction points or points; links are referred to by the terms arcs, edges, or branches. The node-link terminology shall be used throughout this text. A path from the origin to the destination in a network is a list of nodes in which the successive nodes are connected by links in the network.

Dykstra (1984) stated that, in the context of mathematical programming, the term network model is used to define a broad class of techniques useful for solving a wide variety of problems that deal with the geometry of position, where a position may be physical or temporal. Taha (1982) stated that, in practice, network models seem to enjoy tremendous success in solving real-life problems. Taha (1982) also mentioned that perhaps 70 % of the real-world mathematic programming problems can be treated as networks or network-related problems.

The following is a list of typical network models (Ford and Fulkerson 1962, Taha 1982, Dykstra 1984, Gupta 1985, Sedgewick 1988):

— network minimisation model;
— shortest path model;
— maximum flow model;
— minimum cost flow model;
— CPM/PERT.

Although most of the network models can be formulated as linear programming problems, the solving of network models by linear programming is not always advisable. Solutions of network models using dynamic programming are efficient. Some network solutions can be approximated fastest by means of heuristic programming methods.

The most often used model in planning forest road network is the shortest path (or route) model. This model consists of finding the shortest path(s) from source node(s) to destination node(s) through a connecting network. Dreyfus (1969) provided an excellent survey of the shortest path methods. Fox (1978) also reviewed the applications of data structures and computer science techniques in solving the shortest path problems. In the natural resources management field, there is also a wealth of literature relating to the shortest path models; some examples were given by Dykstra (1984). Many special algorithms for solving this type of problems are available (Dreyfus 1969, Fox 1978, Sedgewick 1988). Applications to locating forest road networks are of the following types:

1) Finding the shortest path between two specified nodes. A classic algorithm is Dijkstra's Algorithm (Dijkstra 1959, Denardo and Fox 1979). This is useful in finding the cheapest ways of transporting timber from forest areas to mills (Mandt 1973). These can also be used for finding the shortest paths from a source node to all the other nodes in the network (Carson and Dykstra 1978).

2) Finding the shortest path that passes through certain specified nodes or links. A special case is to find the shortest path which passes each node once and only once in a specified network or subnetwork. This is the so-called Travelling Salesman Problem, which could be applied to the solution of optimum road network for harvesting transportation (Wijngaard and Reinders 1985). Another special case is the so-called Chinese Postman Problem, where the shortest path is found in the case that all the links must be travelled. Nieuwenhuis (1986) stated that this is frequently the case in road inspection and maintenance.

3) Finding the shortest paths between all pairs of nodes in a network. Nieuwenhuis (1986) used the Floyd's triple-loop method to determine the shortest paths between all pairs of nodes in a network; this is useful in calculations of costs for evaluating a planning route. This can also be solved by the n-applications of Dijkstra Algorithm.

Network minimisation model is often useful in planning communication or transportation networks where the objective is to provide some connecting route between every pair of nodes at the lowest possible cost (Dykstra 1984). This model, known as minimum spanning trees, can be used to lay-out a network of roads to service scattered forest stands or compartments so that the total cost of roads is minimised (Kouichi 1966, Dykstra 1984).

Flow optimisation models, including minimum cost flow model, minimum cost capacitated network model, and maximum flow model, are used for determining flows through network, which could be useful in scheduling of traffic within a network, or in the routing of vehicles for timber transportation (Dykstra 1984), and also in improving road quality where flows through certain links (roads) are changed. The shortest path model mentioned above is a special case of a minimum cost flow network model.

CPM (Critical Path Method) and PERT (Project Evaluation and Review Technique) are not considered to be applicable in locating forest roads. These two techniques are designed to help project managers to plan, schedule and control projects, which can be applied to forest road construction (Ramsing 1966).

In addition to network models, techniques from many other mathematical programming methods can also be applied to locating forest road networks. Kirby (1973) demonstrated the use of a mixed-integer programming, which retains many of the features of a standard linear programming model, in planning forest road networks and forest road projects. As stated above, most network models can be formulated as standard linear programming problems and can be thus solved, but it is not advisable to do so (Taha 1982, Dykstra 1984). However, solving these problems by means of dynamic programming is more efficient, and virtually most special algorithms for solving network models are based on dynamic programming — either explicitly (Dreyfus and Law 1977) or implicitly (Sedgewick 1988). Most of the solutions for optimum location of road route using *dynamic programming* depends very much on the starting and end points, or on partitioned basic units such as compartments (Sakai 1984) or grid cells (Douglas and Henderson 1987).

Although mathematical models are used to determine the best (optimum) solution, mathematical formulation can at times be too complex to allow an exact solution to be reached. Even if the optimum solution can eventually be attained, the required computations may be impractically long (Taha 1982). For many other problems, the use of exact mathematical programming techniques cannot be justified, either because of a lack of information or because the problem itself is loosely structured (Dykstra 1976). In these cases, heuristics can be used to develop good (approximate) solutions.

The *heuristic* method of solution relies on experience, inductive reasoning, or intuitive and empirical rules that have the potential to determine an improved solution relative to the current one. Actually, heuristics are search procedures that intelligently move from one solution point to another with the objective of improving the value of the model objective. When no further improvements can be achieved, the best solution attained is the *approximate* solution to the model (Taha 1982). The methods of solution can also be computerised (e.g. Morofsky 1977, Kobayashi 1984, Nieuwenhuis 1986). Due to the great variety of the searching methods, there is no clear-cut procedure for heuristic programming problems and the methodology applicable depends on the problem in question. Although the solution reached by heuristic programming is not the optimum, it is quite close to it (Dykstra 1976, Pulkki 1984).

Network models are useful in optimising the locating of forest roads that connect certain given points. However, this study deals with the problem of locating internal forest roads in a given area where only the starting points are known and the other internal points are unknown. In this case, road locating is difficult as mentioned in section 2.3 (p. 12). The road locating in this

study combines the shortest path model and heuristic programming method so that it can improve the way of cost-benefit analysis and spatial analysis in locating forest roads.

3 Spatial data handling-network routing system

3.1 Overview

As outlined in the preceding sections, the purpose of this study is to develop a method to assist forest managers in planning forest road networks for any forest planning area. Specifically, the spatial data handling-network routing system developed is one that consists of two subsystems: a spatial data handling system and a network routing system.

In handling the spatial data needed for planning a forest road network, a simple and easy method was developed in the course of this study by applying GIS (geographic information system) techniques. Although some types of GIS software packages are available, their prices are high. In addition, they are not built for this purposes. Certain interface software for manipulating and transferring information to the current road network planning system would be necessary if they were to be applied. Otherwise, if a more efficient spatial information management system like GIS were to be available and if it could be adapted to provide the manipulation of the required spatial data, the network routing system could be integrated with it.

Several methods can be used to enter spatial data; e.g. manual encoding, digitising, automatic scanning. The choice of methods depends on the application, the available budget and facilities, the type of data being input, and the database structure. Given the above considerations, the digitising method was chosen for application in the current study. The raster data handling method was adapted since the raster data is easy from the point of view of data storage, data manipulation, spatial analysis and simulation. Because the programs used in this study are modelling-oriented, the raster database was found to be easy to handle by using a programming language such as FORTRAN.

Forest road network planning procedure applied in the present study assumed road locating as its primary task. Besides, the desired road network density was determined during the road locating process, and the desired road standard was selected once the forest road network had been located.

According to the literature review carried out in the course of this study, network models have been found to be applicable in analysing the spatial relationship in the given planning area, and they have been very useful in finding the cheapest routes of terrain transportation, road transportation, road construction and maintenance. However, none of the network modelling methods have been found to be applicable in solving the problem of automating the locating of internal forest roads as formulated in this study. Therefore a special algorithm, called greedy-heuristic algorithm, was developed to automate the road locating.

Three networks were constructed for the purpose of modelling terrain transportation, road transportation, road construction and maintenance. Basically, the networks were constructed by means of a spatial data handling system and by using a grid method, where each cell defined a node, and links were defined as connections between neighbouring nodes only. The spatial data overlays were not the final networks. Since many factors influence the costing of terrain transportation, road transportation, road construction and maintenance, more than one spatial data overlay may be needed to define the costs as the link attributes for each of the networks. However, the spatial data overlays were structured by using the same boundary and the same coordinates, which made the three networks compatible. The links within the networks were determined by the network routing system. The routing for terrain transportation, road transportation, road construction and maintenance was performed using the shortest path model, which finds the lowest cost routes within the networks. The minimum costs of terrain transportation, road transportation, road construction and maintenance between any pair of the nodes in the network were stored in arrays so that they could be read directly from the arrays when needed.

The greedy-heuristic road locating algorithm determines an approximate optimum solution for the problem of locating a forest road network. This algorithm contains searching procedures that extend the forest road network by one most feasible road at one searching iteration, and continue to move from one iteration to another to reduce the total cost of terrain transportation, road transportation, road construction and maintenance by the greatest amount at each iteration, until no feasible road route can be found. A feasible road route is a route for which the road-induced benefit is greater than the cost of road construction. The most feasible road route is the road route which induces the maximum net benefit or maximum ratio of benefit to cost. Network modelling is useful in assisting the calculation of cost and benefit, in carrying out spatial analysis and sensitivity analysis for transportation systems, and in facilitating the selection of desired forest road standards. The use of bounded road catchment area and limited road extending reach, and the development of local network routing model strengthen the application of the network routing system.

The computer programs in the spatial data handling system were written in BASIC programming language (Microsoft Quick Basic... 1987) for microcomputers, while the programs used in the network routing system were written in FORTRAN 77 (Ashcroft et al. 1981, Programming in VAX... 1984) for a mainframe computer respectively due to several reasons. Computation in forest road network routing procedures requires a certain amount of resident memory. Mainframe computers meet the minimum requirements imposed by the computations. On the other hand, the spatial data handling procedures do not require so much computation but they do require more interactive computer time. A microcomputer with certain programming packages is more convenient and efficient.

3.2 Spatial data handling

3.2.1 Digitising method

The principal aim of the digitising method is to convert map-based data into digital form quickly and accurately. The hardware-software components of the spatial data handling system are illustrated in Fig. 38 (Appendix 3, p. 82). The required hardware is a common facility for a microcomputer, on which a digitiser is mounted. The spatial data handling program consists of several modules which have preliminary functions such as those in GIS (i.e. data input, database management, data transformation and data presentation).

Using the digitising method, the two aspects of raster data can be entered simultaneously: spatial position referred to by a pair of coordinates (x, y) and an attribute expressed by a value or a code. The positions are defined by a relative coordinate system. However, there may be two disparities of the coordinate systems between the document sheet and the digitising device: firstly, the axes of the coordinate systems may not be parallel and secondly, the measuring scales may not be the same. These two differences pose the question how to convert the raster coordinates from the digitiser readings.

1) Coordinate transformation

The map sheet is usually secured on the digitiser tablet surface. There may be the difficulty that the coordinate system is not parallel to that of the digitising device. The non-consistency between the coordinate systems can be eliminated by coordinate transformation via programming procedures. According to the theory of analytic geometry (Kindle 1950), there are two steps to accomplish coordinate transformation: translation of axes and rotation of axes.

Let XOY be the map coordinate system and $\Xi O\Psi$ be the digitiser coordinate system (Fig. 4). At least two points need to be digitised: the origin of map coordinate system $O(\xi_o, \Psi_o)$ and another corner point, say $N(\xi_n, \Psi_n)$, where ξ_o, Ψ_o and ξ_n, Ψ_n are the coordinate readings from the digitiser.
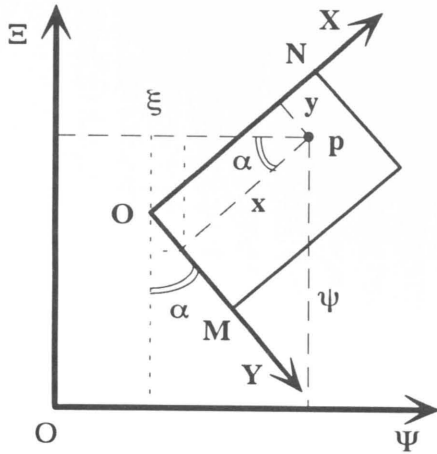
Fig. 4. Coordinate transformation.

Let p be any point in the plane, and let its coordinates referred to the axes of map coordinate system be (x, y), and the coordinates referred to the axes of digitiser coordinate system be (ξ, Ψ). The transformation equations are derived as follows (both translation and rotation).

$$(1) \quad \begin{cases} x = A_x \cdot \xi + B_x \cdot \Psi + C_x \\ y = A_y \cdot \xi + B_y \cdot \Psi + C_y \end{cases}$$

where $A_x, B_x, C_x, A_y, B_y, C_y$ are constants
$A_x = \cos\alpha$; $B_x = \sin\alpha$; $C_x = -\xi_o \cdot \cos\alpha - \Psi_o \cdot \sin\alpha$
$A_y = \sin\alpha$; $B_y = -\cos\alpha$; $C_y = -\xi_o \cdot \sin\alpha + \Psi_o \cdot \cos\alpha$
$\sin\alpha = (\Psi_n - \Psi_o)/\overline{ON}$
$\cos\alpha = (\xi_n - \xi_o)/\overline{ON}$
$\overline{ON} = \sqrt{(\xi_n - \xi_o)^2 + (\Psi_n - \Psi_o)^2}$
α = angle through which the axes of map coordinate system (XOY) are rotated counter-clockwise with respect to digitiser coordinate system ($\Xi O \Psi$)

2) Raster coordinate determination

A way to define the coordinates of raster data is to use the grid system. Raster coordinates are usually integer numbers. When using the digitising method, further manipulations are necessary in getting raster coordinates. The following operations eliminate yet two differences in digitising raster coordinates: the difference between grid cell sizes measured by digitised units and mapping distance; and the difference in map sheet changes along the directions of two axes in a map plane. The change of map sheet size may occur either because of copying by copy machine or because of temperature and humidity changes.

Let l be the size of grid cell, and let L_a and L_b be the planning area length and width measured in number of grid cells; i.e. (Fig. 4) $L_a = \overline{ON}/l$ and $L_b = \overline{OM}/l$, where $\overline{ON}$ is the same as that in expression 1, $\overline{OM}$ is determined by the following:

$$\overline{OM} = \sqrt{(\xi_m - \xi_o)^2 + (\Psi_m - \Psi_o)^2}$$

Then the raster coordinates can be derived as follows:

$$(2) \quad X = INT\left(\frac{x + K_x}{K_x}\right); \quad Y = INT\left(\frac{y + K_y}{K_y}\right)$$

where X, Y are integer numbers as raster coordinates
x, y are map coordinates
INT is a computer function that returns a truncated integer
K_x, J_y are constants in deriving raster coordinates along axes OX and OY

$$K_x = \frac{\sqrt{(x_n - x_0)^2 + (y_n - y_0)^2}}{L_a}$$

$$K_y = \frac{\sqrt{(x_m - x_0)^2 + (y_m - y_0)^2}}{L_b}$$

The raster coordinates (X, Y) in expression 2 refer to a grid cell whose map coordinates (x, y) from expression 1 fall in the ranges of $[X-1, X)$ and $[Y-1, Y)$; i.e. $X-1 \le x < X$, and $Y-1 \le y < Y$.

In addition to the above manipulations, there are several functions available for editing point, line and area, and which enable the user to enter, retrieve and update data interactively. Furthermore, caution must be taken during the digitising process:

1) The document sheet should be secured to the digitiser surface so that the coordinate system of the document sheet is consistent with that of digitising device (this is, however, ensured by the above operations).
2) The document sheet should be kept at the same place until digitising is completed. However, if the document sheet is moved relatively to the digitiser surface, certain modification of the document sheet position has to be done, and this is allowed by the digitising system.
3) Although there are several modes for digitising such as point, switch stream and stream depending on the device (Houston instrument... 1983), the point mode is always recommended.

3.2.2 Raster data estimation

The creation of a clean digital database is a most important and complex task. The usefulness of the spatial data handling system depends on it (Burrough 1986).

As mentioned earlier, the pixel addresses are converted and adjusted automatically into a raster form via the digitising method. However, the pixels on or near the boundary of compartments (a compartment is an area in forest management or harvesting, within which the forest stand, terrain and so on are uniform) may be misallocated or miscoded by carelessness in digitising as such pixels may contain different attributes. Therefore, the boundary polygons or points must be checked cell-by-cell to ensure that their attributes have been correctly estimated. In addition, a proper method for estimating the attributes of a pixel is also important.

There are several ways of determining the attribute value of a grid cell; this may be listed as follows (Fig. 5) (Campbell 1987):

1) *Average* value can be estimated (Fig. 5a) as a single value of the cell for certain type of information such as topographic elevation, forest stumpage in volumes etc.
2) *Predominant category* rule selects the single category that occupies the majority of the cell (Fig. 5b); e.g. the main tree species from among several species in a forest stand represents a cell in the database.
3) *Decisive category* selects the single category that is decisive in the cell, such as road category, river category, etc. (Fig. 5c).
4) *Fixed* dot method selects the category by means of a dot placed in the centre of each cell or randomly positioned within each cell; the category that falls beneath the dot is entered as the category for the cell (Fig. 5d).

To facilitate the encoding of raster data, a transparent grid sheet of that selected cell size can be laid over the map sheet. The grid

$V = (a1 \cdot v1 + a2 \cdot v2 + a3 \cdot v3)/(a1 + a2 + a3)$
where (a1, a2, a3) and (v1, v2, v3) are areas and values

(a) Average

(b) Predominant category

(c) Decisive category

(d) Fixed dot
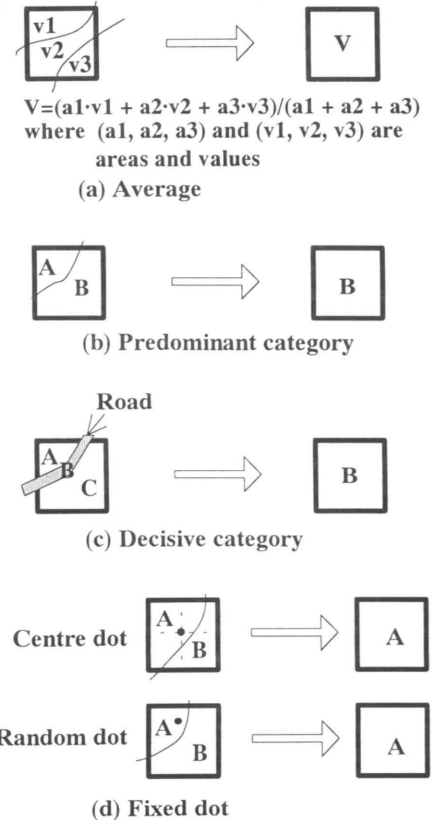
Fig. 5. Data encoding for a grid cell.

sheet permits the user to see which pixel or pixels is being digitised. The grid can be drawn through the programming system if graphic display devices are available. The best way to check that the spatial data has been correctly digitised is to get the computer to redraw the data (Burrough 1986). This is also provided by the current programming system on the same scale as the original, or on any other scale as selected by the user in order that the two maps (i.e. computer drawn and original) might be placed over each other on a light table and compared visually. Any error can be marked on the map and corrected by retrieving the data from the digitising system.

3.2.3 Spatial database management

Since the current study uses raster database structure, it is necessary to convert the vector data (i.e. arcs, polygons and areas) into raster data. The digitiser can be used to digitise a pair of coordinates for a single point, while points are essential elements for defining arcs, polygons and areas in a raster database. The methods on conversion from vector to raster by Pavlidis (1982) were programmed into the digitising system, which included line or polygon fitting for a series of starting and end points, and interior filling for a bounded area.

Data for forest road network planning includes many types (e.g. terrain, forest stand). Each type of data is digitised and encoded separately, which form an overlay. In a raster database, this type of data overlays has coordinate (x, y) addressed database structure (Fig. 6a). The arrays for data overlays are rectangular arrays, containing information both inside and outside of the digitising area.

However, routing programs use information only within the boundaries of the planning area since it was assumed that the planning area does not influence and is not influenced by areas outside it. The spatial data transferred to the network routing system is reorganised so that only the information within the planning area is included. The pixels within the planning area are associated with numbers. Numbering starts from the northwestern corner (top left) and continues to the east (right) and south (down) and ends in the southeastern corner (bottom right). This kind of database consists of a sequence of numbers associated with pairs of coordinates (x, y) and the attributes. The structure of this kind of database is called grid-cell numbered (or coded) database structure (Fig. 6b). It is obviously easier and simpler to use a single code number than to use a pair of coordinates (two values) when referring to a pixel. Furthermore, all the data overlays are integrated and combined into a single data file (Fig. 6c). These numbering and inte-

	X_1	X_2	...	X_N
Y_1	$Z_{111}, Z_{112}, ..., Z_{11K}$	$Z_{121}, Z_{122}, ..., Z_{12K}$	...	$Z_{1N1}, Z_{1N2}, ..., Z_{1NK}$
Y_2	$Z_{211}, Z_{212}, ..., Z_{21K}$	$Z_{221}, Z_{222}, ..., Z_{22k}$	...	$Z_{2N1}, Z_{2N2}, ..., Z_{2NK}$
...	...	...	...	...
Y_M	$Z_{M11}, Z_{M12}, ..., Z_{M1K}$	$Z_{M21}, Z_{M22}, ..., Z_{M2K}$	...	$Z_{MN1}, Z_{MN2}, ..., Z_{MNK}$

(a) (x, y) coordinate addressed

Sequence No	X	Y	Z
1	x_1	y_1	$Z_{11}, Z_{12}, ..., Z_{1K}$
2	x_2	y_2	$Z_{21}, Z_{22}, ..., Z_{2K}$
...	...	...	...
n	x_n	y_n	$Z_{n1}, Z_{n2}, ..., Z_{nK}$

(b) Sequential number associated

Sequence No	X	Y	Z
1	x_1	y_1	$(Z_{111}, Z_{112}, ..., Z_{11K}), (Z_{121}, Z_{122}, ..., Z_{12K}), ...$
2	x_2	y_2	$(Z_{211}, Z_{212}, ..., Z_{21K}), (Z_{221}, Z_{222}, ..., Z_{22K}), ...$
...	...	...	...
n	x_n	y_n	$(Z_{n11}, Z_{n12}, ..., Z_{n1K}), (Z_{n21}, Z_{n22}, ..., Z_{n2K}), ...$

(c) Multi-data overlay

Fig. 6. Raster database structures.

grating operations are performed in a single step. The single numbered data overlay (Fig. 6b) does not exist, as it is transient and it is presented here just for this demonstration. Finally, the data file with multiple-data overlay (Fig. 6c) is transferred into the network routing system.

3.3 Network routing

3.3.1 Road route evaluation

As discussed in the preceding sections, spatial relationships can be expressed by means of network models. Alternative routes for terrain transportation, road transportation, road construction and maintenance can also be constructed through networks. When alternative routes for a road are given, the economical evaluation of the alternatives becomes most important. There are many terms for evaluating a forest road route; e.g. cost, benefit, average terrain transportation distance, exploitation index (Sakai 1983). Cost and benefit are the most common terms used and thus they are applied in this paper.

Let $B_\pi(r)$ and $C_\pi(r)$ be the benefit and cost respectively as functions of r which is the road to be built. The total net benefit can be expressed as follows:

$$(3) \qquad \pi(r) = B_\pi(r) - C_\pi(r) + K$$

where $\pi(r)$ = net benefit as a function of r
K = a constant when r is changed
r = a quantity for measuring road construction, which may be length, density or cost of the road

No physical measures are assigned to the above variables until a specific problem is given. With respect to the independent variable r, a break-even point can be derived by setting the first derivative of $\pi(r)$ in expression 3 to equal zero. That is:

$$\pi'(r) = B_\pi'(r) - C_\pi'(r) = 0, \text{ or}$$
$$(4) \qquad B_\pi'(r) = C_\pi'(r)$$

In terms of marginal analysis, $B_\pi'(r)$ and $C_\pi'(r)$ are marginal benefit and marginal cost respectively. Net benefit is at its maximum when marginal benefit is equal to marginal cost, which is the optimum condition when

locating a forest road network. If the amount of forest roads within the planning area is less than that at optimum condition, increasing the quantity of roads results in a positive value of $\pi(r)$. Thus, extending the forest road network becomes economically feasible if the following condition is true:

$$B_\pi'(r) \geq C_\pi'(r), \text{ or}$$
$$(5) \qquad \pi'(r) = B_\pi'(r) - C_\pi'(r) \geq 0$$

Expression 5 is called the economical feasibility condition of extending a forest road network. Usually, a forest road network is extended to the best alternative of road routes. The best alternative of road routes is the route with the maximum net benefit.

The feasibility condition in expression 5 has one weak point. It neglects the differences in marginal costs when the net marginal benefits are equal for different route alternatives. To take an example: a road inducing a benefit of FIM 2 000 and a cost of FIM 1 900 has the same economical feasibility as a road inducing a benefit of FIM 200 and a cost of FIM 100 according to the feasibility condition in expression 5, because they both return the same net benefit (i.e. FIM 100), but the second is considered to be better because it calls for less investment (cost). The marginal costs in expression 5 include the costs of road construction and maintenance, which have a substantial influence on the location of a forest road network. Therefore, when road routes with different marginal costs are evaluated, the following feasibility condition is used:

$$(6) \qquad \mu = MB(r)/MC(r) \geq 1$$

where $MB(r)$ = marginal benefit, the same as $B'(r)$ in expression 5
$MC(r)$ = marginal cost, the same as $C'(r)$ in expression 5
μ = the ratio of marginal benefit to marginal cost

Basically both conditions in expressions 5 and 6 are identical in finding out the feasible road routes; i.e. if a route is feasible according to the condition in expression 5, it should also be a feasible route according to the condition in expression 6. Using expression 6, the best alternative road route is the route with a maximum ratio of marginal

benefit to marginal cost.

The road locating procedure in the present study extends the forest road network iteration by iteration to approach the optimum situation. At a particular iteration, a road with the maximum ratio of benefit to cost may not yield the maximum net benefit whereas a small marginal cost with a small net benefit may produce a big ratio of benefit to cost. However, the total net benefit is maximised when the whole routing process is completed, since the routing in subsequent iterations continues to return benefits.

In evaluating a route for a road, the costs and benefits can be determined by the method illustrated in Fig. 7 (Kobayashi 1984). For a given planning area A, a route $\overline{ab}$ (Fig. 7) is assumed for the road. The resultant benefit is defined as the reduced cost of transportation within the catchment area achieved by building a road along the assumed route. For instance, terrain transportation from point c (Fig. 7) is previously along route $\overline{cc_0}$ but a shorter route $\overline{cc_1}$ is taken when the new road $\overline{ab}$ is built. The benefit at point c by using the new road $\overline{ab}$ is a cost difference; i.e. the cost of terrain transportation along route $\overline{cc_0}$ minus the cost of all transportation along route cc_1bc_0 including terrain transportation along $\overline{cc_1}$ and road transportation along $\overline{c_1b}$ and $\overline{bc_0}$. The marginal benefit from building a road along route $\overline{ab}$ is the total reduced transportation cost from all the points such as point c within the road catchment area. The marginal costs are the costs of building and maintaining the road if it is constructed.

The construction of a road is economical only if the costs of building the road can be covered by the total benefits resulting from the cheaper transportation within the catchment area. The road catchment area is illustrated by Fig. 7, for example, where point c belongs to the catchment area but point d does not.

The calculation of costs and benefits in evaluating a road route is one of the tasks of the network routing system. The network routing system (Fig. 36 in Appendix 1.1, p. 76) contains procedures for forming networks, finding shortest paths, and locating roads, and other input/output procedures for transient data files and communi-
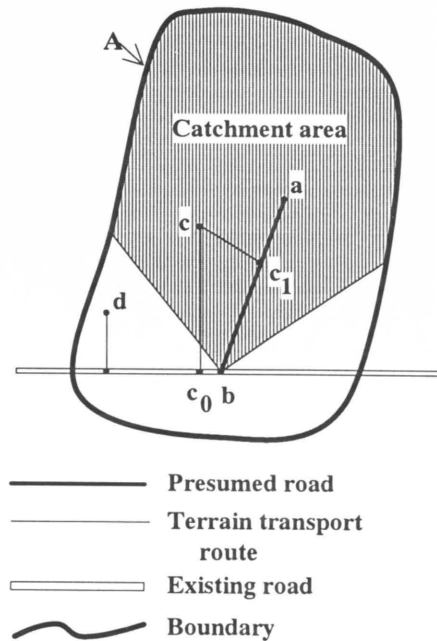

Fig. 7. Evaluating a presumed road route.

— Presumed road

— Terrain transport route

— Existing road

— Boundary

cating with the spatial data handling subsystem. The first procedure in the network routing system called DINFO performs data input and preliminary network formation operations. Data input includes information transformation from the spatial database to the network routing system and data query from other sources (e.g. expert knowledge or documented information concerning the costs). The nodes and links for all the transportation networks are defined at the same time. The algorithm in DINFO is problem-dependent; its basic principles are presented in the next section (section 3.3.2, p. 25). The second procedure called SPMD is used to determine the shortest path matrices containing the cheapest routes for road construction, terrain transportation and road transportation (section 3.3.3, p. 28). The determination of the shortest path matrices consumes the major part of computer resources by the current system. In order that several alternatives for the

location of a road network might be found, it may prove necessary to run the network routing programs more than once. During first run, the shortest path matrices are determined and can be stored in disk or tape files. Later, the program takes the data of the shortest path matrices from the files, and this demands less time. This is why a procedure called IOI is included for intermediate input/output. A procedure called FRNET contains the greedy-heuristic road locating algorithm, which finds out the best location for a road network (section 3.3.4, p. 29). Finally, the results are output to files through a separate procedure called OFF, which includes some operations for outputting the results of the applications as well. The above procedures may take different forms in different planning problems; thus, only their general principles are presented in the following sections.

3.3.2 Transportation networks encoding and definition

Three transportation networks are needed for terrain transportation, road transportation, road construction and maintenance. The elements of a network are its nodes and links. In mathematical expressions, let $G = (N, A)$ be a connected directed network formed by means of the grid method within the given planning area. N is the set of n elements called nodes of G, $N = \{1, 2, ..., n\}$, where n is equal to the total number of nodes. A is any subset of $N \times N$. Elements of A are called links. The following special definitions and encoding methods for transportation networks are used in programming the network routing system (procedure DINFO in Fig. 36, Appendix 1.1, p. 76).

1) Nodes

Nodes in networks are determined by a grid method. A node is usually used to represent a cell but differs from a cell in that a node is not referred to by an area but by a point in the cell centre. The same numbers for cells are associated with nodes. The mathematical expressions for the nodes are defined below:

$N = \{i \mid i$ is a node in the planning area$\}$;

$R = \{i \mid i$ is a road node, it carries out road transportation, and it can be a road node, a landing place, a railway or a waterway; railway or waterway nodes should not have crosswise functions; i.e. terrain transportation to or from them should not be allowed, except for landings$\}$;

$O = \{i \mid i$ is an entry node, it is a road node that is located at the boundary of the planning area connecting inside and outside transportation$\}$;

$B = \{i \mid i$ is a branching road node permitting further connections by a new road$\}$;

$S = \{i \mid i$ is a positive land node, it permits the construction of a road or road structure such as bridge, culvert, etc. but i is not a road node$\}$.

A separate data overlay is used for encoding the above defined nodes as shown in Fig. 8. The relationships between the sets of nodes are also illustrated in Fig. 8. Sets R, O, B and S are subsets of N. Set B is a subset of R. Sets R and S are exclusive.

Non-land nodes are not included in running the network routing programs but they are listed in the table as they are a part of the entire planning area.

All the nodes for the road systems are encoded in the set R by numeric values from 1 to 8. The set R includes the nodes of current existing roads, planned roads, structures like bridges, culverts and so on. Therefore, set R increases in the road locating process when new roads are selected.

The entry (or exit) nodes in set O are located on the boundary of the given planning area, from which hauling by road is continued. The entry nodes may include the nodes such as current existing roads, landings from railway or waterway, or mills. All the entry nodes in set O are contained in set R.

All the nodes in set R are categorised into extendible and non-extendible nodes. The extendible road nodes are included in set B, from which new roads can be connected as branches. Such extendible existing road nodes are coded with numeric values from 1 to 4. If an extendible road node contains a structure, a maximum number of two branches is allowed to be lead to the node; otherwise a maximum number of four nodes can be branched from the node. When the branching reaches the limit, no more branching is allowed from the extendible road node whose code is changed from 1 to 8, or from 2 to 7, or from 3 to 6, or from 4 to 5. It becomes a

Code	Explanations	R	S	O	B
$-\infty$	non-land (omit afterwards)				
-1	river crossable		positive		
0	forest land		land		
1	planned road extendable				extendable
2	current existing road extendable				road
3	structure as an extendable road				
4	entry-exit road extendable	forest		entry or	
5	entry-exit road non-extendable	road		exit	
6	structure as non-extendable road				
7	existing road non-extendable				
8	planned road non-extendable				

Fig. 8. Encoding for the land types and the nodes of transportation networks.

non-extendible road node and is taken out of the set **B**.

The nodes in set **S** are non-road nodes through which construction would be possible. They are so-called positive land nodes for building roads or structures and they contain nodes such as crossable rivers and forest lands. The crossable river nodes are river nodes where a structure, such as a culvert, bridge and so on, could be established for linking up the transportation on both sides of the river. A crossable river node, coded to be 1, is recoded to be 3 if a crossing structure is planned with one road connection. It is recorded to be 6 if a crossing structure with two road connections is planned.

As consequences of the above descriptions, the set **R** is encoded with a number from 1 to 8, **S** with a number 1 and 0, **O** with a number 4 and 5, and **B** with a number from 1 to 4. All the nodes in the network of the whole planning area are encoded by means of the spatial data handling system.

2) Links

Links are defined as connections between neighbouring nodes only. Therefore, a node can have at most eight links with its neighbouring nodes. There are no link between non-neighbouring nodes. For example, the node i in Fig. 9a has only eight neighbouring nodes (i.e. A_1, A_2, A_3, A_4, a_5, a_6, a_7, and a_8), which form eight links: (i, A_1), (i, A_2), (i, A_3) (i, A_4), (i, a_5), (i, a_6), (i, a_7), and (i, a_8). The following symbols are used to denote neighbouring nodes:

$D_8 = \{1,2,3,4,5,6,7,8\}$ is a set of 8 direction codes: numbers from 1 to 8 correspondingly represent east, northeast, north, northwest, west, southwest, south and southeast.

(a) Links of a given node
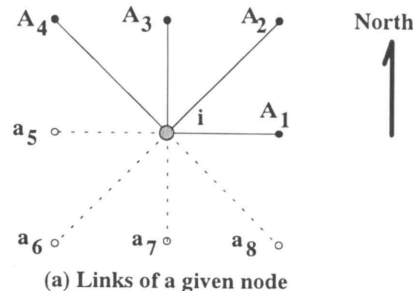
Overlay	Direction	Links
Layer 1	East	(i, A_1)
Layer 2	North-East	(i, A_2)
Layer 3	North	(i, A_3)
Layer 4	North-West	(i, A_4)

(b) Record by four overlays

Fig. 9. Encoding for links of a given node.

$E_i = \{e_{i1}, e_{i2}, ..., e_{i8}\}$ is a set of neighbouring nodes around node i, where e_{ik} are the node labels in the eight directions, $k \in D_8$; e.g. in Fig. 9a, $e_{i1} = A_1$, $e_{i2} = A_2$, ..., $e_{i8} = a_8$.

The geometric length of a link from node i to one of its neighbouring nodes, say $j \in E_i = \{A_1, A_2, A_3, A_4, a_5, a_6, a_7, a_8\}$, is defined as follows:

$$(7) \quad l_{ij} = \sqrt{(x_i - x_j)^2 + (y_i - y_j)^2}$$

where (x_i, y_i) and (x_j, y_j) are the coordinates of node i and its neighbouring node j respectively. When the attribute values of the two neighbouring nodes are given, the average value of a link is determined by the average of values of the neighbouring nodes as follows:

$$(8) \quad z_{ij} = (z_i + z_j)/2$$

where z_i, z_j are the given attribute values of node i and its neighbouring node j respectively

z_{ij} = the average value of the link (i, j)

If z_i, z_j and hence z_{ij} are the value per unit of length, the total physical value can be determined as follows:

$$(9) \quad c_{ij} = l_{ij} \cdot z_{ij}$$

where c_{ij} = the total physical value of link (i, j), which may be distance, cost, etc.

3) Networks

Networks are needed to model the spatial relationships for road construction, terrain transportation and road transportation. The networks for road construction and terrain transportation contain the same nodes as those in the network of the whole planning area; i.e. all the nodes in **N**. The network for road transportation contains the same nodes as those in set **R**, which is updated when new roads are added during the road locating process. The links for all the networks are defined as the connections between neighbouring nodes only, as mentioned earlier.

The attribute values for each of the nodes in the networks are captured into a spatial database. There may be more than one attribute for every node in each of the three networks, and these are encoded into spatial data overlays. A single data overlay containing a data matrix of the same size as the network records one type of attribute. In the network routing system, links are established through a series of operations by checking the neighbouring nodes of each node, after which they are associated with the attribute values. If all the links in a given network have to be determined, it is sufficient that four, instead of eight, neighbouring nodes of each node are searched. For instance, only four links to the neighbouring nodes (A_1, A_2, A_3, A_4) of node i in Fig. 9 are found in node i; i.e. (i, A_1), (i, A_2), (i, A_3) and (i, A_4). The remaining four links need not be searched in node i since they are searched and determined in the neighbouring nodes of node i; i.e. link (i, a_5) is encoded in node a_5, (i, a_6) in node a_6, (i, a_7) in node a_7, and (i, a_8) in node a_8. The attribute value for a link is calculated from the attributes of the nodes at the ends of the link by expressions 7, 8 or 9. These nodes for defining links are called link nodes.

However, extreme terrain conditions, such as river, steep slopes, big rocks, may restrict terrain transportation and road construction. Extreme terrain can be recorded on links between neighbouring nodes where restrictions are found. In addition to the attribute value, four other data overlays are necessary for the restricted links. These are as follows:

— direction 1: west-east;
— direction 2: southwest-northeast;
— direction 3: south-north;
— direction 4: southeast-northwest.

These directional restrictions are encoded in the same way as that shown in Fig. 9. The attribute values of such restricted links are modified by the above data correspondingly. If the restrictions along two (opposite) ways of a link are different, eight data overlays may be needed: two data overlays, for each of the above four directions, record the links in the two opposed ways.

The link geometric lengths in the networks are calculated and put into a matrix of size $n \times n$, which is useful in determining the cost or distance for a link or a path in the networks. Each cell of the matrix is addressed by its subscript of i and j, representing the physical values of the link from node i to j. The data structure of this type of matrices is given in Fig. 10, where l_{ij} is the

From	To				
	1	2	3	...	n
1	l_{11}	l_{12}	l_{13}	...	l_{1n}
2	l_{21}	l_{22}	l_{23}	...	l_{2n}
3	l_{31}	l_{32}	l_{33}	..	l_{3n}
...	...	...	...	...	...
n	l_{n1}	l_{n2}	l_{n3}	...	l_{nn}

Fig. 10. Data structure of the link length matrix.

physical value of the link from node i to j if nodes i and j are neighbouring nodes in a network, for all $i \neq j$; and $l_{ii} = 0$; otherwise l_{ij} is set to infinite.

3.3.3 Minimum cost routing

The calculation of costs and benefits in evaluating a road route is easier once the cheapest routes between all pairs of nodes have been determined for terrain transportation, road transportation and road construction. One popularly used algorithm for finding the shortest paths between every pair of nodes in a network is Floyd's algorithm (Floyd 1962). While Floyd's triple-loop operating method is simple to use (Nieuwenhuis 1986), it was found that by operating this algorithm with the network data in this study the triple-loop had to be run more than once to get the final solution. Another of the most efficient algorithms in solving the shortest route problems is Dijkstra's Algorithm (Dijkstra 1959). To find the shortest paths between every pair of nodes in a network, one simply applies a streamlined version of Dijkstra's algorithm for n times (Fox, 1978), where n is the number of nodes in the network. By comparing the n-applications of the Dijkstra's algorithm with Floyd's algorithm, Dreyfus (1969) reported that the former requires roughly 1.5 times the time consumed by the latter. As Floyd's triple-loop had to be run twice to obtain the final solution, it is clear that the n-applications of Dijkstra's algorithm is faster. Although Hoffman and Winograd (1972) made the Floyd's algorithm faster, still running the triple-loop twice is not as fast as running the n-applications of

Dijkstra's algorithm once. Therefore, the Dijkstra's Algorithm was adapted to solve the shortest path problems in the present study. Although Dijkstra's algorithm could be improved by using heaps (Spira 1973) or buckets (Denardo and Fox 1979), these improvements sophisticate the algorithm, and the maintaining and reforming of the heaps or buckets also consume the computer time. This study used the n-applications of Dijkstra's algorithm (Fox 1978) because of its ease in programming. The shortest path algorithms in this section use the following definitions and expressions:

$P_{ij} = \{i = i_0, i_1, ..., i_{m'} = j \mid i \neq j\}$ is a path from node i to j, containing an ordered sequence of distinct nodes, where (i_{k-1}, i_k) is a link for each $k = 1, ..., m'$ (Ford and Fulkerson 1962).

If the path is directed (i.e. it leads from i to j), it is called a chain. The total length of a path can be calculated by using the following formula:

$$(10) \quad C(P_{ij}) = \sum_{k=1}^{m'} \left(C_{i_{k-1}i_k} \right) = \sum_{k=1}^{m'} \left(l_{i_{k-1}i_k} \cdot z_{i_{k-1}i_k} \right)$$

$Z = (z_i)$ is an array of the link node attributes, in terms of cost, distance or the like, where z_i is the attribute value for node i, which is needed to determine the link attribute, $i \in N$.

$L = (l_{ij})$ is a link length matrix, where l_{ij} is the length of the link (i, j) as defined by expression 7, for all $j \in E_i$; and $l_{ii} = 0$; otherwise $l_{ij} = \infty$, $i \in N$, $j \in N$.

$P = (p_{ij})$ is a path matrix, where p_{ij} is the node preceding j on the shortest path from node i to j, $p_{ij} \in N$, $i \in N$, $j \in N$.

$C = (c_{ij})$ is a cost matrix, where c_{ij} is the minimum cost, distance or the like, from node i to j.

$T = \{t \mid t \in N\}$ is the set of nodes with temporary labels.

The array $Z = (z_i)$ and matrix $L = (l_{ij})$ are given, and $P = (p_{ij})$ and $C = (c_{ij})$ are unknown matrices to be derived. The matrices P and C are called the shortest path matrices (Nieuwenhuis 1986).

The data structures of the shortest path matrices thus derived, P and C, are similar to that in Fig. 10. Each cell in the matrices is independently addressed by its subscript of row number i and column number j. A cell value p_{ij} in the shortest path matrix P represents the node number preceding node j

on the shortest path from node i to j. All the nodes on the shortest path from node i to j can be found by tracing backward from node j through the matrix P:

$$j, p_{ij}, p_{ip_{ij}}, ..., i$$

or

$$(11) \quad j = j_{m'} \to j_{m'-1} \to ... \to j_1 \to j_0 = i$$

where $i \neq j$, $j_k = p_{ij_{k+1}}$, $k = 0, 1, 2, ..., m' - 1$

A cell value c_{ij} in the length matrix C represents the physical length of the shortest path from node i to j. The C matrix contains the lowest costs and is thus called the cost matrix. The mathematical expressions of the shortest path matrices for terrain transportation, road transportation and road construction are defined as follows.

— $CR = (cr_{ij})$ and $PR = (pr_{ij})$ are the cost matrix and path matrix for forest road construction and maintenance, where cr_{ij} is the minimum cost of the road between nodes i and j, $i \in N$, $j \in N$ and pr_{ij} is the node preceding j on the shortest path from node i to j.

— $CS = (cs_{ij})$ and $PS = (ps_{ij})$ are the cost matrix and path matrix for terrain transportation, where cs_{ij} is the minimum cost of terrain transportation between nodes i and j, $i \in N$, $j \in N$ and ps_{ij} is the node preceding j on the shortest path from node i to j.

— $CH = (ch_{ij})$ and $PH = (ph_{ij})$ are the cost matrix and path matrix for road transportation, where ch_{ij} is the minimum cost of road transportation between nodes i and j, $i \in R$, $j \in R$ and ph_{ij} is the node preceding j on the shortest path from node i to j.

There are two types of the shortest path algorithms used in this study. The reasons are as follows.

1) To find the shortest paths between every pair of nodes in a connected network. The n-applications of Dijkstra's algorithm is adapted as Algorithm A1 listed in Appendix 1.3 (p. 77) and programmed into the procedure SPMD (Fig. 36 in Appendix 1.1, p. 76), which initialises all the shortest path matrices: CR, CS, CH, PR, PS, PH.

2) To find the shortest paths from a source node to all other nodes in a connected non-directed network. The shortest path matrices for road transportation CH and PH are initialised by the existing road nodes, but they must be updated when new road nodes are selected and inserted into a road

transportation network. For a non-directed network, the determination of the shortest paths between every pair of nodes in the road transportation network including both new and old road nodes can be completed when the shortest paths from every new road node to all old road nodes are found and their opposite paths are determined by tracing backward these paths. Dijkstra's algorithm is adapted for this purpose as Algorithm A2 listed in Appendix 1.4 (p. 77). The Algorithm A2 is used in the procedure FRNET (Fig. 36 in Appendix 1.1, p. 76). However, in a directed network, updating the shortest path matrices for road transportation can not be achieved by Algorithm A2, since the paths are directed and hence the opposite path can not be simply found just by tracing backward along the path from a new road node to an old road node. Algorithm A1 can be applied to initialise again the shortest path matrices CH and PH in a directed network containing both new and old road nodes for the convenience of simple and easy programming.

The procedures and algorithms listed in Appendix 1 do not mean exactly the same thing. A procedure may use one or more algorithms. The procedure SPMD (Fig. 36 in Appendix 1.1, p. 76), for example, uses Algorithm A1 three times for initialising the shortest path matrices of terrain transportation, road transportation and road construction correspondingly. The procedure FRNET contains mainly Algorithm A3 (section 3.3.4), but it also uses either Algorithm A2 for updating, or Algorithm A1 for initialising again, the shortest path matrices CH and PH depending on whether the network is directed or not. All the Algorithms are outlined in Fig. 37 (Appendix 1.2, p. 76), which shows also the relations between the algorithms and procedures.

3.3.4 A greedy-heuristic algorithm for locating forest roads

Theoretically, the most economic location of a forest road network can be found by applying the exhaust enumeration method; i.e. by selecting the best one from among all possible combinations of the constructed nodes and links. In practice, enumeration cannot be realised due to the explosive, combinatorial nature of the mathematics involved in it. The number of alternatives

(expressed as $2^{n(n-1)/2}$, where n is the total number of nodes) is enormous if the size of the network is large. Haggett et al. (1977) demonstrated that many of the combinations are apparently inefficient and could be eliminated. Therefore, the objective in solving this type of problem is to reduce the vast number of possible solutions to a feasible sub-set of real interests. A greedy-heuristic algorithm was developed in this study to assist the identification of the best routes in extending a forest road network. The greedy-heuristic algorithm embodies the following assumptions:

1) The objective in road locating is to obtain a road network that minimises the total cost of terrain transportation, road transportation, road construction and maintenance in performing the forest road related activities.
2) Total transportation is carried out in at most three parts as follows (Any combination of this sequence can be taken. The terrain transportation is assumed to take place in a distant area, and road transportation is for accessing to the distant forest area):
   — terrain transportation within the planning area;
   — road transportation within the planning area;
   — transportation outside the planning area.
3) All types of transportation take place along the shortest routes for any of the three modes.
4) Combined transportation takes place along the route with minimum combined total transportation cost no matter what type of transportation is applied.
5) At most two types of transportation modes are used for transporting products to/from any place within the planning area although more transportation modes may be used outside the planning area, and these are considered to be external transportation.
6) Roads are always extended from a road node in current road network to a non-road forest land node along the cheapest route.

In addition to the definitions and symbols in the preceding three sections, the greedy-heuristic algorithm uses the following mathematical expressions:

CO = (co_i) is an array of the road transportation costs outside the planning area, where co_i is the cost of the road transportation outside the planning area and bordering the planning area at node $i \in O$.

CT = (ct_i) is an array of the total transportation cost for each node $i \in N$, where ct_i is the cheapest total cost combining all forms of transportation for node i.

PT = $[RT, OT]$ is a path array for combined transportation (including terrain transportation and road transportation), where $RT = (rt_i)$ and $OT = (ot_i)$. Combined transportation was assumed to take place in the cheapest way along route i → rt_i → ot_i. rt_i is the nearest road node between terrain transportation and road transportation. ot_i is the nearest entry node at the boundary of the planning area. $i \in N$, $rt_i \in R$, $ot_i \in O$.

BS = (bs_i) is an array, where $bs_i \in B$ is called the nearest branching road node to node i such that the cost of road construction and maintenance is the lowest between bs_i and positive land node $i \in S$.

GCT = grand total of transportation costs for the entire area. GCT' is a temporary value.

μ = a ratio of marginal benefit to marginal cost, its initial value is set to 1. μ' is a temporary variable for μ.

π = net benefit. π is 0 at beginning. π' is a temporary variable for π.

w = a node in S, where the best route for a road (with the biggest benefit-cost ratio) is defined from w to its nearest branching road node $bs_{6w} \in B$ as defined in array BS. w' is its temporary value.

The FRNET procedure in the network routing system (Fig. 36 in Appendix 1.1, p. 76) consists mainly of the greedy-heuristic road locating algorithm. Before entering the procedure FRNET, the procedure SPMD containing Algorithm A1 (see Appendix 1.3, p. 77, and section 3.3.3, p. 28) determines the shortest path matrices for the costs and paths for terrain transportation, road transportation and road construction: CR and PR; CS and PS; CH and PH, which are necessary in calculating the cost and benefit. The greedy-heuristic road locating algorithm, listed as Algorithm A3 in Appendix 1.5 (p. 77), includes the following steps (Fig. 11):

1) Initialisation

Since the greedy-heuristic algorithm has a nature of heuristics which determines an improved solution relative to the current one, the status of the current network must be known. In the beginning, the current network is the initial network in the given planning area. The initial values are deter-
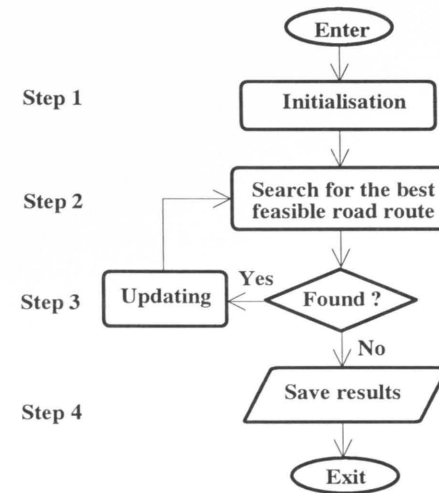

Fig. 11. General order of road locating procedures when using the greedy-heuristic algorithm.
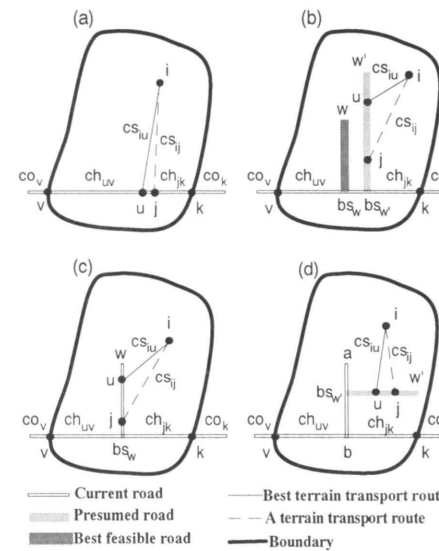

Fig. 12. Thematic illustration of road locating when using the greedy-heuristic algorithm.

mined for the following besides the shortest path matrices mentioned above.

The initial sets of R, O, S, B can be entered or coded through the spatial data handling system. These sets are updated at each of the subsequent iterations.

For any node $i \in N$, the initial value of the total transportation cost is calculated and the initial paths are found by the combined transportation modes along the cheapest route i → rt_i → ot_i. As the above assumptions imply, the total transportation is supposed to take place along the cheapest way by one of the combinations of three parts: (i) terrain transportation specified by the end nodes i and rt_i, whose minimum cost and path are found in the matrices CS and PS; (ii) road transportation within the planning area specified by end points rt_i and ot_i, whose minimum cost and route are found in the matrices CH and PH; and (iii) road transportation outside the planning area referred by the entry node ot_i, whose cost is found in the array CO. A series of searching and calculating is needed to determine the end points for the different types of transportation for a given node $i \in N$. The purpose of this manipulation is actually to determine two arrays: the path array PT and the cost array CT. The searching and calculating sequences can be explained as follows (Fig. 12a). From a node i in the planning area, the timber transportation may be carried out along many routes such as i → j → k ..., where $i \in N$, $j \in R$, $k \in O$. However, only one of these routes is the cheapest route for combined transportation from node i; i.e. the route along i → u → v ..., where $i \in N$, $u \in R$, $v \in O$, and which has to be found out. The cost of total transportation consists of three parts: terrain transportation cost cs_{ij}, road transportation cost within the planning area ch_{jj}, and road transportation cost outside the planning area co_k. Once the cheapest route of total transportation from node i is found out (i.e. nodes $u \in R$ and $v \in O$ are determined), the minimum cost of total transportation from node i is calculated as $ct_i = cs_{iu} + ch_{uv} + co_v$. Meanwhile, the values of the path nodes u and v are assigned to their corresponding elements in array PT; i.e. let $rt_i = u$ and $ot_i = v$. The total cost of transportation for the whole planning area, denoted as GCT, is

derived by summing up the lowest costs of transportation for each of the node $i \in N$; that is:

$$(12) \quad GCT = \sum_{i=1}^{n} ct_i$$
$$= \sum_{i=1}^{n} \left(\min_{j \in R, k \in O} \{cs_{ij} + ch_{jk} + co_k\} \right)$$

All the elements in array **BS** are assigned with the labels of the nearest branching road nodes. A path with the lowest road cost from any forest land (non-road) node $i \in S$ to its nearest branching road node $k \in B$ as defined in the array **BS** can be directly found from the shortest path matrices **CR** and **PR**.

2) Finding the best feasible road route

This is achieved by a searching procedure that presupposes some road routes at first, then evaluates these routes according to their induced benefits and costs, and finally selects a feasible road route with the maximum benefit to cost ratio. The searching procedure should not change the status of the current road network. Most of the variables are temporary variables at this stage.

The feasibility condition in expression 6 (p. 23) is used to evaluate a road route. The minimum value of the benefit to cost ratio for a feasible road route is set to be 1; correspondingly, its minimum net benefit is set to be 0. The value of net benefit is used as a tie-breaker when two presupposed road routes produce equal benefit to cost ratios.

The positive land nodes are temporarily stored in set **S′**. By taking a node w′ out of set **S′**, a road route in matrix **PR** from w′ to its nearest branching road route $bs_{w'}$ is presupposed as a part of the road network and these nodes on this presupposed road route (from w′ to $bs_{w'}$ in Fig. 12b) are then placed in set **R′**, where $bs_{w'}$ is defined in array **BS**.

As shown in Fig. 12b, the transportation from node i may take a shorter way when the new set of presumed road nodes between w′ and $bs_{w'}$ are supposed to be a part of the road network. A route along $i \rightarrow j \rightarrow k \dots$ from node i is supposed to be any one of the transportation routes passing the presumed road nodes, where $i \in S$, $j \in R'$, $k \in O$. The total cost of transportation from node i is

the sum of cs_{ij}, ch_{jk}, and co_k. It should be noticed that the road transportation cost within the planning area ch_{jk} includes two parts: one is the cost of road transportation along the presumed road nodes in **R′** from j to $bs_{w'}$, and the other is the cost of road transportation along the previous road nodes in **R** from $bs_{w'}$ to k (Fig. 12b). Among these possible routes, the cheapest way of transportation from node i through the presumed road nodes in **R′** need to be found out; it is specified by the nodes $u \in R'$ and $v \in O$, and the cost of transportation is calculated as $ct_i' = cs_{iu} + ch_{uv} + co_v$. The minimum cost of transportation from node i (considering both the previous road nodes in set **R** and the presumed road nodes in set **R′**) is then determined as the smaller value between ct_i' and ct_i. The calculation of the total cost of transportation for the whole planning area under the presumed road network can be expressed mathematically as follows:

$$(13) \quad GCT' = \sum_{i=1}^{n} ct_i'$$
$$= \sum_{i=1}^{n} \left(\min_{j \in R', k \in O} \{cs_{ij} + ch_{jk} + co_k, ct_i\} \right)$$

where **R′** $= \{i \mid i$ is a node on the path in the matrix **PR** from the node $w' \in S'$ to its nearest branching road node $bs_{w'}$ found in array **BS**, and $i \in S\}$

CT′ $= (ct_i')$ is a temporary array for **CT**, where ct_i' is the minimum total cost of transportation from a node $i \in N$ under presumed road network including the nodes in both sets **R** and **R′**

The net benefit and the ratio of marginal benefit to marginal cost are then derived as follows:

$$(14) \quad \pi' = (GCT - GCT') - cr_{ij}$$

$$(15) \quad \mu' = \frac{GCT - GCT'}{cr_{ij}}$$

where $cr_{ij} =$ the minimum cost of road construction and maintenance found in the matrices **PR** and **CR** between nodes i and j, $i = w' \in S$ and $j = bs_{w'} \in B$

If the value μ' of the current ratio of marginal benefit to marginal cost is greater than the previous value μ, more benefit is to be gained by including the set of presumed

road nodes in set **R′** into the previous road network as formed by the nodes in set **R**. Hence, the presupposed road route is selected. Marginal benefit is calculated as $(GCT - GCT')$ and marginal cost is cr_{ij}. The presupposed road route is determined by the route in the matrix **PR** from the node $w' \in S'$ to its nearest branching road node $bs_{w'} \in B$ found in array **BS**. If this route is selected, the value of w′ is assigned to w which records the best road route. Meanwhile, the variables μ and π are also updated with the new values for this selected road route and the previous selection is disregarded.

If μ' is equal to μ, the value π' of the marginal net benefit is used as a tie-breaker; i.e. if π' is greater than π, the presupposed road route is selected, if not, the presupposed road route is passed over and the values of w, μ, and π remain unchanged.

If μ' is less than μ, the presupposed road route is not feasible and is neglected. The previous selection remains valid.

Finally, the node w′ is dropped out of S′. If the set S′ is not empty, another node is taken out of S′ and the above procedure is repeated. When the set S′ is empty, searching is completed. If w is not infinite, the best feasible road route is found, and road locating proceeds to step 3 for updating the road network and so on. The presumed road route between nodes w and bs_w in Fig. 12b, for example, is found to be the best feasible road route. Then the road network is updated with this best feasible road route as that in Fig. 12c. If w is infinite, no feasible road route is found. Searching is then stopped and the program is terminated at step 4.

3) Updating

If the best feasible road route is found, this route should be inserted into the current road network. The updating is also a preparation for (and always returns to) the next searching and selecting procedure in step 2.

The best feasible road route is determined by the route in matrix **PR** between node $w \in S$ and its nearest branching road node $bs_w \in B$ found in array **BS**, which is shown in Fig. 12b. The set of nodes on the best

feasible road route, denoted as **R′**, are positive land nodes contained in set **S**. The nodes in set **R′** are inserted to sets **R** and **B**, and deleted from set **S**.

When a series of new road nodes have been inserted, these nodes become part of the road network, and transportation along these road nodes becomes possible. The shortest path matrices of road transportation are then updated with these new road nodes by means of Algorithm A2 (Appendix 1.4, p. 77) if the network is directed, or by Algorithm A1 (Appendix 1.3, p. 77) if the network is not directed.

The path array **PT** and cost array **CT** of total transportation are updated, and the total cost of transportation for the whole planning area is calculated as follows:

$$(16) \quad GCT = \sum_{i=1}^{n} \left(\min_{j \in R', k \in O} \{cs_{ij} + ch_{jk} + co_k, ct_i\} \right)$$

where **R′** $= \{i \mid i$ is a node on the path in the matrix **PR** from the node $w \in S$ to its nearest branching road node bs_w found in array **BS**, and $i \in S\}$

The calculation in expression 16 is just one of the calculations for expression 13 in step 2, but this calculation is done for the best feasible road route only.

After extending the road network, the branching road nodes in set **B** are changed so that the nearest branching road nodes in the array **BS** can be renewed. The intermediate results at this stage may be useful for monitoring the road locating procedure and are then output. The updated road network (e.g. that in Fig. 12c) is used as the initial network in the following searching and selecting procedures. The program is returned to step 2 for next searching and selecting procedure, which continues the evaluation of another set of presupposed road nodes as shown in Fig. 12d.

4) Saving the final results and exiting the procedure

The final output data may need further programming work depending on the user's requirements. Flexibility remains with the user. The program is terminated once all the data output has been completed.

3.3.5 Average terrain transportation distance

The average terrain transportation distance is the main variable in the costing of terrain transportation, which is related to road spacing and road network density. The relationship between average terrain transportation distance and road network density is useful in investigating transportation networks. Conventional studies on the relationships between road network density and average terrain transportation distance are based on assumptions such as the following (Matthews 1942, von Segebaden 1964):

i) Roads are straight lines, parallel and equidistant.
ii) Terrain transportation routes are straight lines.
iii) Terrain transportation routes are perpendicular to their nearest road.
iv) Forest stand and road usage are uniform within the whole planning area.

Under such ideal conditions (Fig. 1, p. 10), the following relationship exists:

$$(17) \quad D_B = 10000/(4 \cdot d_r)$$

where D_B = the bee-line average terrain transportation distance under the above basic assumptions, (m)
$d_r = L_r/A$
d_r = road network density, (m/ha)
L_r = the length of road (m)
A = the total area (ha)

In reality, however, most road networks do not satisfy all the above assumptions. For practical applications, the following coefficients are introduced for describing the deviations from the above conditions.

1) Equality of road spacing in a network

Parallel and equidistant roads are very efficient in covering forest lands in the sense that the forest roads are a system of lines serving the forest area, but transportation cannot be performed unless the roads are connected and also joined to the further transportation roads outside the planning area. Typical forest road networks are usually neither parallel nor equally spaced but interconnected or branched (Pulkki

1984). The deviation of average terrain transportation distance from that in expression 17 is described by the following expression:

$$(18) \quad \sigma_e = D_A/D_B$$

where σ_e = equality coefficient of road spacing
D_A = the bee-line average terrain transportation distance under basic assumptions but excluding assumption (i)

$$(19) \quad D_A = \frac{\int_A D \, dA}{\int_A dA} = \frac{1}{A}\int_A D \, dA$$

where $A = \int_A dA$ is total area (ha)

dA = differentiated area (ha) for integration
D = terrain transportation distance (m) along a straight-line route and perpendicular to the nearest road for a differentiated area dA; i.e. along the dashed line in Fig. 13, where the two end points are in the centre of area dA and its nearest road node respectively; and the value of D is determined by expression 7 (p. 27)

Road
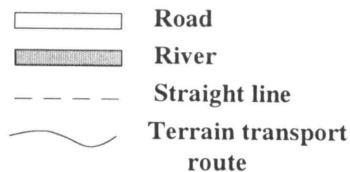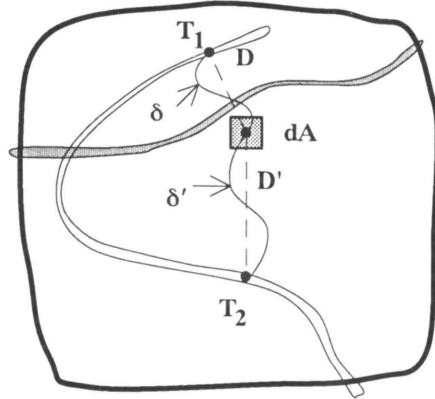River
Straight line
Terrain transport route

Fig. 13. Schematic drawing on the variation of terrain transportation routes.

The equality coefficient describes the magnitude of deviation of the road network from the basic model in assumption (i) (referring to Fig. 1, p. 10); i.e. roads are straight lines, parallel and equidistant. The coefficient takes the value 1 if assumption (i) is true. Otherwise, its value is greater than 1. The road network should in this case be structured as evenly as possible; i.e. the equality coefficient of road spacing should be as low as possible.

In practice, expression 19 can be estimated by expression 20 where the planning area is divided into subunits; e.g. grid cells or compartments.

$$(20) \quad D_A = \frac{\sum_{i=1}^{n} (D_i \cdot a_i)}{\sum_{i=1}^{n} a_i} = \frac{1}{A} \sum_{i=1}^{n} (D_i \cdot a_i)$$

where $A = \sum_{i=1}^{n} a_i$ is the total area (ha)

n = total number of subareas divided from the planning area
a_i and D_i are area (ha) and bee-line terrain transportation distance (m) for subarea unit i, i = 1, 2, ..., n

2) Consistency of terrain transportation routes

The assumed terrain transportation route for the minute area dA in Fig. 13 is perpendicular to the nearest road at point T_1, but due to the terrain restrictions in the form of a river, terrain transportation for area dA has to be performed along the route to road point T_2 instead. In the present study, the terrain transportation routes were determined by means of the lowest total transportation (terrain transportation plus road transportation) cost instead of the minimum terrain transportation cost only. Therefore, a consistency coefficient was introduced to describe the extent by which terrain transportation routes differed from the routes perpendicular to the nearest road:

$$(21) \quad \sigma_c = D_R/D_A$$

where $D_R = \frac{1}{A} \sum_{i=1}^{n} (D_i' \cdot a_i)$

σ_c = consistency coefficient of terrain transportation
D_R = bee-line average terrain transportation distance (m) under the basic conditions except for condition (iii)
D_i' = bee-line terrain transportation distance (m) for subarea unit i, but it may not take the route perpendicular to the nearest road

The consistency coefficient is a factor describing the deviation of the road network from the basic conditions, resulted not only from terrain restriction but also from certain economical requirements such as minimising the total transportation costs. The value of the consistency coefficient is equal to 1 if all terrain transportation is conducted perpendicularly to the nearest roads. Otherwise, this value is greater than 1.

3) Vicinity

The above calculations of average terrain transportation distance are based on the assumption that the quantities of terrain transportation are the same for all the subarea units. In reality, the quantities differ from unit to unit. The average terrain transportation distance has to be calculated by considering this variation for the different subareas. A vicinity coefficient is employed to take the diverse terrain transportation quantities into account in calculating the average terrain transportation distance as follows (with the size of loads per travel assumed to be equal for every transportation load):

$$(22) \quad \sigma_v = D_Q/D_R$$

where $D_Q = \frac{1}{Q} \sum_{i=1}^{n} (D_i' \cdot q_i \cdot a_i)$

$Q = \sum_{i=1}^{n} (q_i \cdot a_i)$

σ_v = vicinity coefficient
D_Q = bee-line average terrain transportation distance (m) taking into account variation in transportation quantities and terrain etc.
Q = total transportation quantity for entire area

D_i', q_i, a_i are bee-line terrain transportation distance (m), quantity (m³/ha), and area (ha) for subarea unit i, i = 1, 2, ..., n

The vicinity coefficient describes mainly the closeness of the road to the user. It is better to locate the roads closer to heavy users. This vicinity coefficient σ_v modifies the idea of equality factor σ_e so that a better road network may not include the evenly located roads but may include deviations that roads are located closer to the road users. The value of vicinity coefficient is 1 if either the roads are equidistant to their users or the quantities of terrain transportation are even. Otherwise it may be greater or less than 1 depending on the location of the road network with respect to its users.

4) Winding routes in terrain transportation

Real transportation routes are not straight lines but curved (the route indicated by δ' in Fig. 13). The winding coefficient is defined by the following expression:

(23) $\sigma_w = D_q/D_Q$

where $D_q = \dfrac{1}{Q} \sum\limits_{i=1}^{n} (\delta_i' \cdot q_i \cdot a_i)$

D_q = average terrain transportation distance derived from real (curved) terrain transportation routes

σ_w = winding coefficient

δ_i' = real terrain transportation distance for subunit i, i = 1, 2, ..., n

The winding coefficient is usually due to terrain restrictions, and its value is greater than or equal to 1. The value of the winding coefficient is greater if the variation in terrain condition is greater, and vice versa.

5) Overall spatial coefficient

As a total description of the spatial variation of terrain transportation routes, the average terrain transportation distance can have the following relationship with the road network density.

(24) $D_q = \sigma \cdot 10000/(4 \cdot d_r)$

where $\sigma = \sigma_e \cdot \sigma_c \cdot \sigma_v \cdot \sigma_w$
         $= D_q/D_B$
σ = overall spatial coefficient

The overall spatial coefficient describes the total deviation of the average terrain transportation distance from that calculated under basic conditions. The physical meaning of σ is indicated by the individual factors such as equality, consistency, vicinity and winding as described in the above texts.

3.3.6 Desired forest road standard

In locating a forest road network by means of the network routing system, forest roads are assumed to be of the lowest standard. The standard of forest roads can be determined after the location of a forest road network has been determined. Due to the complexity of the task, the determination of forest road standard is treated in a limited way in this study, which is regarded as being an extended application of the network routing system. The methods used in determining forest road standards are referred to the literature (e.g. Matthews 1948, Porpaczy and Waelti 1976, Sundberg and Silversides 1988).

The forest road standard is selected so as to minimise the total cost of road construction and transportation. Generally, higher standard forest roads require higher road costs, but bring about lower transportation costs. There is a trade-off between road costs and transportation costs when determining the standard for a forest road; it is usually simplified to determining the desired vehicle speed. To achieve a higher average designed speed requires better quality roads and hence expensive road construction. On the other hand, high speed transportation uses less transportation time and hence results in lower transportation costs. The best road quality, as measured by the optimum velocity of vehicles, is determined so that the total cost of road construction and timber transportation is minimised.

From the literature (Sundberg and Silversides 1988), the cost of road construction and the moving cost of vehicles are assumed to be

determined by equations 25 and 26. When the total cost of road construction and road transportation, i.e. $C_r + C_h$, is minimised, the optimum velocity of vehicle is then obtained from expression 27.

(25) $C_r = k_0 + k \cdot V$
(26) $C_h = (2 \cdot C_{mt} \cdot Q_f)/(q_p \cdot V)$

(27) $V = \sqrt{\dfrac{2 \cdot C_{mt} \cdot Q_f}{k \cdot q_p}}$

where C_r = total cost of road construction
        C_h = total cost of vehicle moving
        C_{mt} = moving cost of vehicle per unit time
        Q_f = timber flow quantity
        q_p = payload of available vehicle
        V = desired vehicle velocity
        2 = constant due to two-way travelling of vehicles

        k_0 and k are other constants

Forest roads should be of such quality as will support the desired vehicle velocity to minimise the total cost. In deriving the desired vehicle velocity, the network routing system can be applied to calculate the timber flow quantities, which is a parameter in expression 27.

3.4 Road locating procedure improvements

3.4.1 Bounded road catchment area

The purpose in using a bounded road catchment area is to improve the result of road locating and to reduce computing time of the road locating procedure. As mentioned earlier, a road catchment area is the area around the road that supports all transportation within the planning area. Any point whose transportation is carried out on the road is part of the catchment area of the road. A road catchment area is usually limited to a given planning area. A bounded road catchment area is a road catchment area within which terrain transportation distance is limited by a maximum value.

When the road catchment area is large, the heavy weight of far-away areas in calculating the cost and benefit overlooks the influence of the neighbourhood area of the road. The accumulative calculations for the large road catchment area, particularly for areas far away from the road, produce a large benefit.

This large benefit results in inefficiency of road locating in two aspects.

Firstly, the influence of the road cost differences due to terrain difficulties in the neighbourhood area of the extended road is neglected. Since both cost and benefit are used in evaluating the route of a road, the influence of the costs is reduced when the difference of costs is relatively small in comparison to that of the benefits. Consequently, a road may be located crossing over an area with relatively high road investments being involved .

Secondly, a road is always located in the direction towards the centre of the whole road catchment area. Fig. 14 illustrates a road route located in both unbounded and bounded road catchment areas. The located road route in the unbounded road catchment area in Fig. 14a is turned towards the centre of its catchment area. It is apparent that there is an imbalance of terrain transportation distance on the two sides of the road, which may be referred to as reflecting low road system efficiency (von Segebaden 1964). When the planning area is large, the

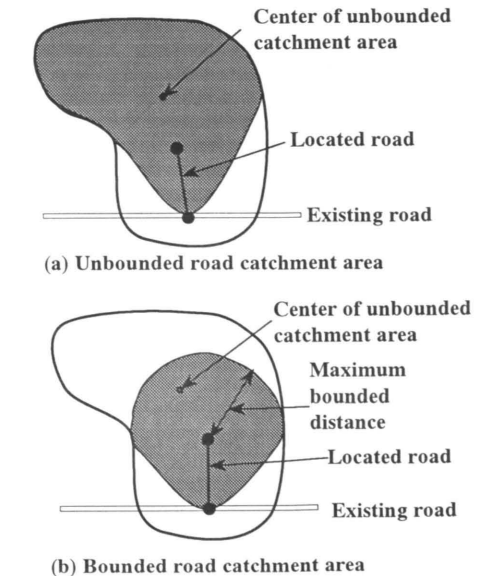(a) Unbounded road catchment area

(b) Bounded road catchment area

Fig. 14. Influence of road catchment area on road locating.

imbalance of terrain transportation distance occurs more often.

When a bounded road catchment area is used, the benefit is calculated within the limit of the bounded road catchment area so that the calculated value of benefit is restricted, and thus the effect of the above two shortcomings can be reduced (refer to Fig. 14b), and the computing time is also less. For the problem of locating a road with the lowest quality class, it is important for the road to be located to serve well its neighbourhood area and induce a lower investment. Therefore, road catchment area, particularly in large areas, should be of the bounded type.

3.4.2 Limited road extending reach

Road extending reach is regarded as the maximum road extending length. When applying an unlimited road extending reach, a road network is extended iteration-by-iteration from the current road network to a positive land node, where the road extending reach can be of any length as long as the extended road satisfies the feasibility condition (expression 6, p. 23). If the length of the extended road at each iteration is so defined as not to exceed the maximum value, one can expect that less computing time is needed in arriving at the similar results. This predetermined road extending length is called limited road extending reach. Nieuwenhuis (1986), for example, used the limited road extending reach in such a way that the extended road length at one iteration of the road locating process was limited within a road service zone.

When using the limited road extending reach, Algorithm A3 (Appendix 1.5, p. 77) can be modified at step 2.1 by setting:

S' = {set of positive land nodes from which the distances to their nearest branching road nodes do not exceed the predetermined maximum road extending reach}

It is apparent that S' is a subset of S. The number of nodes contained in set S' is smaller than that in set S. According to the limited road extending reach, not all the nodes in set S, but a smaller amount of

nodes in a subset S', have to be checked at each iteration so that the total computing time is reduced.

The road locating procedure is flexible in using the limited road extending reach; i.e. the road extending reach can be switched, as necessary, between a fixed value (limited) and an infinite value (unlimited). This flexibility is very useful in case of locating a road crossing over extreme terrain like a river, for example. When a road has to cross over extreme terrain, the cost of road construction is high. If the road extending reach is limited to a small value, the marginal benefit (i.e. reduced transportation cost) from such a road extension may not be enough to cover the marginal cost of road extension and consequently road locating is terminated. However, by reassigning an infinite value to the road extending reach, road extension can take into account any feasible length of road route. Limited road extending reach is used in the routing of areas without extreme terrain restrictions, while unlimited road extending reach is used in case of extreme terrain restrictions such as river nodes. After crossing an extreme section of the terrain, limited road extending reach is reapplied. The road extending process is thus continued until the optimum condition is obtained. Therefore, the flexible use of limited road extending reach in the road locating procedure meets the needs of both goals; i.e. reduced computing time and evaluation of the road route without missing feasible alternatives.

3.4.3 Local network routing model

The local network routing model is intent to reduce the consumption of computer resources by the road locating procedure and to increase the capacity of the network routing system for coping with large road planning areas. The improvements achieved by the application of bounded road catchment area and limited road extending reach provide motivation for developing the local network routing model. As stated earlier (section 3.3.3, p. 28), the shortest path matrices are the two matrices containing the shortest routes between each pair of nodes in the network for a given planning area. If the

principles of the bounded road catchment area and limited road extending reach are used, it is sufficient to establish the shortest paths from a node to all the nodes in its neighbourhood area only. The local network routing model is a technical improvement, which determines the shortest path matrices from each node to all other nodes in the neighbourhood area instead of the whole planning area, and then locates the roads through this type of local shortest path model by using the bounded road catchment area and limited road extending reach. If the neighbourhood area is smaller in size than the whole planning area, the requirement of computer resources by the local network routing model can be reduced in terms of time and space. The local network routing model involves the following definitions and modifications.

1) Neighbourhood region

The neighbourhood region is usually referred to by an area node. The neighbourhood region around a node i is a circular area that is defined by a radius and the coordinates of this node i. In the definition of the network created by the grid system, a square area that covers the neighbourhood region is easier to handle the spatial data for finding the shortest paths in this neighbourhood region. In this study, the same size was used for both the bounded road catchment area and the neighbourhood region. Let m_{br} be the radius of the neighbourhood region. Then the neighbourhood region around node i can be found in a square area whose top left corner node has the area coordinates $(x_i - m_{br}, y_i - m_{br})$ and whose bottom right corner node has the area coordinates $(x_i + m_{br}, y_i + m_{br})$. This square area is used as the neighbourhood region in the following.

2) Regional coordinate system

A relative coordinate system called regional coordinate system is used to describe the locations in a neighbourhood region. For the sake of contrast, the coordinate system for the whole area is called the area coordinate system. Similarly, a node referenced by regional coordinates is called a regional node, and a node referenced by area

coordinates is called an area node. The orientation of the axes in the regional coordinate system is the same as that in the area coordinate system, and the origin of the regional coordinate system is the currently referred area node i. Thus the nodes in the top left corner and bottom right corner of the neighbourhood region around the referred node i have the regional coordinates $(-m_{br}, -m_{br})$ and (m_{br}, m_{br}) respectively. There is a relationship between the area coordinate system and the regional coordinate system. Let node $j \in N$ be in the neighbourhood region of node $i \in N$. The area coordinates of node i are (x_i, y_i). Node j has area coordinates (x_j, y_j) and regional coordinates (ξ_{ij}, Ψ_{ij}). Then the relationship between the area coordinates and the regional coordinates of node j can be expressed as follows:

$$(28) \quad \begin{cases} x_j = x_i + \xi_{ij} \\ y_j = y_i + \Psi_{ij} \end{cases}$$

3) Regional node labels

A regional number is associated with each of the nodes in the neighbourhood region of area node i. The regional number for area node j in the neighbourhood region of area node i is called a regional label, denoted by J. From here on, the lowercased letters i, j, k are used when referring to different area nodes and the uppercased letters I, J, K are used when referring to different neighbourhood region nodes. Regional labels are sequential numbers, starting from the top left corner node towards the right and down to the bottom right corner node of the neighbourhood region. Let M_{br} be the number of unites measured by raster coordinates for the distance m_{br} as converted by expression 2 (p. 20). Then the node with regional coordinates $(-M_{br}, -M_{br})$ is associated with number 1, the node $(-M_{br}+1, -M_{br})$ is numbered 2, ..., the node $(M_{br}-1, M_{br})$ is numbered n_m-1, and the node (M_{br}, M_{br}) is numbered n_m. $M = \{1, 2, ..., n_m\}$ is used to denote the set of nodes in the neighbourhood region of an area node, where the numbers in the set M are the neighbourhood region labels, and n_m is the total number of nodes in the neighbourhood region: $n_m = (2 M_{br} + 1)^2$.

4) Conversion between region and area labels of a node

The regional numbering system is independent of the area numbering system. However, the connection between regional labels and area labels is defined through matrix: $H = (h_{iJ})$, where h_{iJ} = area node label for a given regional node J if it is in the neighbourhood region of node i; otherwise $h_{iJ} = 0$, $i \in N$, $J \in M$. When the regional label J for a node in the neighbourhood region of node i is given, its area label is found to be h_{iJ} from matrix H. On the other hand, it is also necessary to find the regional label for a node j (area label) in the neighbourhood region of node i (area label). A simple method is to use a matrix $n \times n$ in size, in which the regional label J of each node $j \neq i$ at the neighbourhood region of node i is registered in column j and row i ($J \in M$, $j \in N$, $i \in N$), but this matrix has a size of $n \times n$, which does not fit the idea of a local network routing model. An easy way for finding the region label J of a node j in the neighbourhood region of node i without the matrix of size $n \times n$ is to use the coordinate relationship in expression 28 as both area labels and regional labels are assigned to nodes by referring to their coordinates. If nodes $i \in N$ and $j \in N$, which have area coordinates (x_i, y_i) and (x_j, y_j) respectively, are given, then the regional coordinates (ξ_{ij}, Ψ_{ij}) of node j in the neighbourhood region of node i can be derived from expression 28. If $|\xi_{ij}| > M_{br}$ or $|\Psi_{ij}| > M_{br}$, the node j is not within the neighbourhood region of node i. Otherwise, the node j is within the neighbourhood region of node i and its regional label can be calculated by expression 29 as follows:

$$(29) \quad J = (2 M_{br}+1)(M_{br}+\xi_{ij})+(M_{br}+\Psi_{ij}+1)$$

If $\xi_{ij} = 0$ and $\Psi_{ij} = 0$, then $J = (2 M_{br}+1)M_{br}+(M_{br}+1) = J_0$. Element h_{iJ_0} in matrix $H = (h_{iJ})$ represents the current node i; i.e. $h_{iJ_0} = i$, which is located in the centre of the neighbourhood region.

5) Link matrix

A link matrix of the order $n \times n$ is used in the primary network routing model as shown in Fig. 10 (p. 28). This is simple to program because the shortest path matrices are of the same order $n \times n$. However, this link matrix structure of the order $n \times n$ is not applied in the local network routing model. Since the links are determined for neighbouring nodes only, a smaller set can be used for the neighbouring nodes of node i. This is defined by the following link matrix:

$L = (l_{ij})$ is the link matrix, where l_{ij} is the length of the link (i, e_{ij}), $i \in N$, $e_{ij} \in E_i$, $j \in D_8$; E_i and D_8 are the sets of neighbouring nodes and their direction codes as defined in section 3.3.2 (Fig. 9, p. 26).

6) Shortest path matrices

The shortest path matrices according to the local network routing model can be expressed as follows:

$P = (p_{iJ})$ is a path matrix, where p_{iJ} is the node preceding J on the shortest path from node i to J, $p_{iJ} \in M$, $i \in N$, $J \in M$.

$C = (c_{iJ})$ is a length matrix, where c_{iJ} is the shortest distance from node i to J, $i \in N$, $J \in M$.

The data structures for the shortest path matrices according to the local shortest path model are different from those of the primary shortest path model. Each cell of the matrices is addressed by its subscripts of row number i and column number J, where row number $i \in N$ is an area node label and column number $J \in M$ is a regional node label in the neighbourhood region of node i. Cell value $p_{iJ} \in M$ in the shortest path matrix P is a regional label for the node preceding the regional node $J \in M$ on the shortest path from area node $i \in N$ to regional node $J \in M$. The area labels of regional nodes $J \in M$ and $p_{iJ} \in M$ are h_{iJ} and $h_{ip_{iJ}}$ respectively as found from matrix H. All the nodes on the shortest path from node $i \in N$ to $J \in M$ can be found by tracing backward through the matrix P as follows:

$$(30) \quad J = J_{m'} \rightarrow J_{m'-1} \rightarrow ... \rightarrow J_1 \rightarrow J_0 \Leftrightarrow i$$

where $i = h_{iJ_0}$
$i \neq h_{iJ}$
$J_k = P_{iJ_{k+1}}$, which is the neighbourhood region label of the node on the shortest path, $k = 0, 1, 2, ..., m'-1$

$m'-1$ = total number of nodes on the shortest path between nodes i and h_{iJ}

7) Algorithm modification

To determine this type of shortest path matrices mentioned above by the local shortest path model, Algorithm A1 (Appendix 1.3, p. 77) is modified into Algorithm A4 (Appendix 1.6, p. 78). The greedy-heuristic road locating Algorithm A3 (Appendix 1.5, p. 77) is adapted into Algorithm A5 (Appendix 1.7, p. 79) in accordance with the local network routing model. This modification is made to matrix manipulation only, the procedure's structure is the same as that in algorithm A3.

The shortest path matrices for terrain transportation and road construction are initialised through Algorithm A4; $CR = (cr_{iJ})$ and $PR = (pr_{iJ})$; $CS = (cs_{iJ})$ and $PS = (ps_{iJ})$, where $i \in N$, $J \in M$. However, road transportation is usually not limited by the road catchment area boundary as they cover the whole planning area and go even beyond it. Thus, the shortest path matrices for road transportation are still initialised by Algorithm A1: $CH = (ch_{ij})$ and $PH = (ph_{ij})$, where $i \in R$, $j \in R$. The size of set R increases with an increase in the planning area, but the size of set R accounts for about 20 percent of the size of set N, depending on the road network density. The requirement of computing resources is not so high as that according to the full size of set N as in the shortest path matrices for terrain transportation and road construction. Both Algorithm A4 and Algorithm A1 were programmed into procedure SPMD (Fig. 36, p. 76) for initialising the shortest path matrices in the local network routing model.

The road locating procedure (FRNET in Fig. 36, p. 76) in local network routing model contains the algorithm A5. To update the shortest path matrices of road transportation, either Algorithm A1 or A2 is used depending on whether the network is directed or not, as explained in section 3.3.3 (p. 28).

In summary, the local network routing model uses the Algorithms A1, A2, A4 and A5 as discussed above; this is also outlined in Fig. 37 (Appendix 1.2, p. 76).

8) Symbols for bounded road catchment area and limited road extending reach

In locating a forest road according to the local network routing model, one must apply the bounded road catchment area and limited road extending reach. Thus, the local network routing model uses two additional symbols for the bounded road catchment area and limited road extending reach as follows:

β = radius of bounded road catchment area.
ρ = limited road extending reach.

The bounded road catchment area and limited road extending reach can also be applied in the primary network routing model as described earlier. If this is done, Algorithm A3 (Appendix 1.5, p. 77) should be modified in the steps where the bounded road catchment area and limited road extending reach are used (Algorithm A5 in Appendix 1.7, p. 79).

9) Remarks on local network routing model

When the bounded road catchment area and limited road extending reach are used, the local network routing model can make better use of the programming system in two ways. Firstly, in each of the n-application of Dijkstra's Algorithm, finding all the shortest paths within a smaller neighbourhood region (Algorithm A4) consumes less time than finding all the shortest paths in the network of the whole area (Algorithm A1). Secondly, the computing time for finding all the shortest paths from every node to all other nodes in the neighbourhood region has a linear relationship with (i.e. is directly proportional to) the size of set N in the network of the whole area, instead of being proportional to the third power of the size of set N according to the primary network routing model, since the size of neighbourhood region is independent of the size of the whole area. This resultant requirement of computing time is more reasonable and practical.

4 Practical application

4.1 General

The preceding chapters have outlined the principles involved in developing the spatial data handling-network routing system in general. It is useful to apply thus developed system into a road planing practice in order that its application capabilities and limitations might be tested. Therefore, a case study was undertaken using data from a practical road planning project. In addition to the primary network routing model, the local network routing model, bounded road catchment area and limited road extending reach were applied to achieve alternative solutions and different performances. The case study results were discussed and analysed over their applicability. Selecting the road standard was considered as an extended application of the network routing system.

4.2 Road locating case study source

4.2.1 The selected road planning area

A part of Ylikemi Forest District in northern Finland belonging to the Kemijärvi State Forests owned and managed by the National Board of Forestry was selected (Fig. 15) in order to demonstrate the method presented in the previous chapters. This area, some 559 hectares in size, is currently served on its western boundary by a north-south oriented forest road with a total length inside the area of 3 192 meters. The average terrain transportation distance is 1 598 meters. Timber transportation continues for about 80 km down the road from the exit of the area (in the south-western corner of the map) to Kemi where the closest wood industry conglomeration is located. The labour resour-
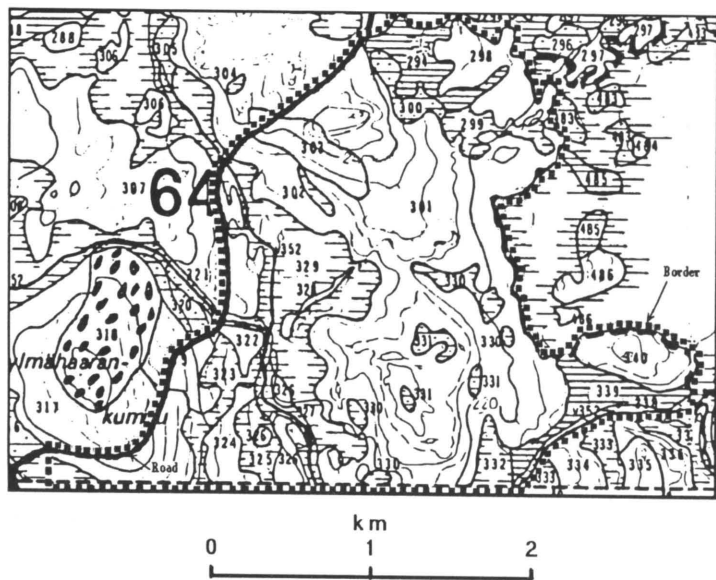

Fig. 15. Forest management planning map of the selected road planning area.

Table 1. Some information about each forest management planning compartment (numbers in parentheses are partially covered in the planning area).

Compartment	Total area ha		Density m³/ha		Species 1/10			Cutting Methods
	Digital	Inventory	Stand	Cut	Spruce	Pine	Birch	
294	18	(79)	10	10	0	10	0	Thinning
298	24	24	70	70	8	0	2	Clear Cut
299	9	9	0	0	–	–	–	Uncut
300	7	7	30	30	8	0	2	Clear Cut
301	260	(310)	70	40	8	0	2	Clear Cut
302	2	2	0	0	–	–	–	Uncut
303	15	16	140	140	10	0	0	Clear Cut
307	14	(109)	110	50	9	0	1	Clear Cut
317	16	(74)	60	30	8	0	2	Clear Cut
319	9	(16)	40	40	7	0	3	Clear Cut
321	4	(9)	100	100	7	0	3	Clear Cut
322	3	(5)	60	60	7	1	2	Clear Cut
323	13	13	0	0	–	–	–	Uncut
324	10	10	50	50	7	0	3	Clear Cut
325	8	8	0	0	–	–	–	Uncut
326	9	9	50	50	7	0	3	Clear Cut
327	9	9	40	40	6	0	4	Clear Cut
328	3	2	60	0	7	0	3	Uncut
329	58	(76)	0	0	–	–	–	Uncut
330	8	8	0	0	–	–	–	Uncut
331	5	5	10	0	7	0	3	Uncut
332	7	7	0	0	–	–	–	Uncut
338	10	(15)	60	60	7	0	3	Clear Cut
339	18	18	10	10	0	8	2	Thinning
340	18	18	70	70	7	0	3	Clear Cut
352	2	1.6	0	0	–	–	–	Uncut
Sum	559	558.6	29 390	20 040	6.7	1.0	2.3	

ces are available from the neighbourhood of the area (about 30 km away from the area). The terrain conditions, as on most of Finnish forest lands, are characterised by a mixture of mineral soils and peat lands that are relatively flat and swampy. There is a stream in the south-western part of the area, where a culvert, costing about FIM 26 000, is needed if a road is to be built across it. The forest lands are divided into compartments. There are 26 compartments in the selected area, some of which are peat lands with little or no forest (Table 1). The total forest stumpage volume is 29 390 m³ from which 20 040 m³ is going to be cut during the next few years (within 5 years according to the forest management planning schedule). The main species are Norway spruce (67 %), birch (23 %) and Scots pine (10 %). The majority of the stands are at the age of about 200 years. The reason why this area was selected is that a preliminary forest road planning has been recently made for the area. Thus, it was possible to make a comparison and test the validations of the results of the method used in the present study.

4.2.2 Costs and factors

The effects of various factors affecting decision making in forest road network planning are simply interpreted into costs and benefits using the present values. Most of the cost data for the case study were adapted from a practical forest road plan where the cost estimations were made by experienced road planners familiar with the planning area. The forest management planning documents, together with topographic maps for the selected planning area, were collected and also used for making detailed compartment-specific estimates. The costs and factors of terrain transportation and road transportation were based on the Finnish forest wage agreements and extracted from relevant tariff schedules (Metsä- ja uittoalan ... 1988, Puutavaran autokuljetusmaksut 1988, Puutavaran metsätraktorikuljetusmaksut 1988). The transportation costs were categorised into costs for labour and timber transportation in the terrain and by road respectively. The costs of road construc-

tion and maintenance were estimated by road planning experts.

The costs of travel by the labour force were dealt with differently from those of timber transportation. People performing forest-related activities have to travel in the forest. The costs of travel by the labour force are different for situations with and without a road; i.e. travel costs are influenced by roads. This is why the cost of travel by the labour force should be taken into account.

The determination of travel costs by the labour force depends on many factors. These costs are assumed to be a function of the following variables:

1) Travelling distance.
2) Travelling means:
   — short distance: on foot, by boat, on skis, on horseback, by bicycle;
   — motor vehicles: moped, motorbike, snow scooter;
   — private car;
   — employers' car.
3) Amount of work in man-days.

The distance travelled is the geometric distance measured on a map from compartment to compartment. A distance matrix was constructed for determining the distance between nodes (grid cells on raster map) in the network models used in this study. The different rates between chain saw users and other workers were also considered in this situation. In the event that there is spatial variation in the travelling means within the entire area for the activities to be implemented in each of the compartments, an overlay should be constructed to provide this information. However, for the application on hand, it was assumed that travel by road took place using the employers' cars, and that travel in the terrain was on foot.

Travel by the labour force was estimated in man-days per hectare compartment-specifically for the following forest-related activities:

— harvesting operations;
— site preparation;
— clearing of felling areas;
— preliminary tending of young stands;
— planting;
— direct seeding;

— further tending of young stands;
— drainage;
— fertilising.

For each of the above activities, the following three types of work were included:

— manual work;
— planning;
— supervision.

Daily earnings were assumed to be FIM 300 for all kinds of work. Loggers' work site productivity was assumed to be about 10 m^3 per work day. The work site activities of loggers included felling, delimbing, bucking and sorting as well as planning and supervision. The work involved in the other activities was estimated by experienced road planners.

In most of the cases, wood transportation accounted for most of the use of the road system. Two types of wood transportation modes were considered separately in costing the transportation routes: terrain transportation and road transportation of wood. The following variables were taken into account in determining *road transportation cost of wood.*

1) Distance.
2) Amount of wood to be transported.
3) Wood assortment:
   — softwood pulpwood (green), 3 m;
   — softwood pulpwood (half-dry), 3 m;
   — spruce logs (green);
   — spruce logs (half-dry);
   — pine logs (green);
   — pine logs (half-dry);
   — hardwood pulpwood (green), 3 m;
   — hardwood pulpwood (half-dry), 3 m;
   — birch logs (green);
   — birch logs (half-dry).
4) Loading site class:
   — site class 1;
   — site class 2;
   — site class 3.

In the routing process, the transportation distances within the area are outputs of the shortest path arrays if the start and end points of a route are given. To determine the total road transportation costs, road transportation both within and outside the area

were also taken into account. The amount of wood to be transported was estimated in m^3/ha according to forest inventory documents. The wood assortments are recorded in the forest management planning documents for each of the compartments and these were included as separate data overlays in the spatial database.

The *terrain transportation cost of wood* was determined according to the following variables:

1) Distance.
2) Amount of wood to be transported.
3) Logging method:
   — clear cutting;
   — first thinning;
   — other thinning.
4) Wood assortment:
   — softwood pulpwood (2.6—3.6 m);
   — softwood logs (<7 m);
   — hardwood pulpwood (2.6—3.6 m);
   — birch logs.
5) Terrain class (average).
6) Cutting volume class:
   — logging trail spacing;
   — cutting volume.

The geometric distance between any given pair of nodes was found out directly from the shortest path matrices of terrain transportation. The variable of distance in determining terrain transportation costs was classified using an interval of 100 meters. The amount of wood to be transported was estimated in m^3/ha according to forest inventory documents. There are four terrain classes I, II, III, and IV. The average terrain class along a given route was obtained by using expression 37 (p. 49), and rounding the result to the nearest integer.

Wood transportation may be carried out by different types of vehicles. At this application, the forwarder transportation mode was assumed for terrain transportation and truck transportation mode for road transportation.

The costs of road construction and maintenance were estimated according to a previous road planning draft for the selected planning area and the Yearbook of Forest Statistics 1988 (Uusitalo 1989). Rough cost

classifications were made using the following properties of terrain as spatial variables:

— mineral soil forest land;
— shallow peat land;
— deep peat land;
— special construction; e.g. a culvert is necessary for crossing the stream located in the area.

The transportation costs were determined by means of separate subprograms for travel by the labour force, road transportation of wood, and terrain transportation of wood. The basic wood transportation rates both in the terrain and by road were recorded in a data file. The rates applied for travel by the labour force were entered by means of a BLOCK DATA procedure using FORTRAN programming source codes. Most of the costing variables were coded into quantitative values and captured into different data overlays, which could then be easily accessed by the road network routing programs. The distances between any given pair of points were calculated by applying the minimum cost routing method.

4.2.3 Spatial data overlay and mapping

Spatial database management is mainly concerned with collecting the necessary data from maps or documents, entering and converting these data into digital form, and finally transferring the digital information into the network routing system.

In establishing a raster database, the raster data resolution must be properly selected. In terms of grid cells, bigger size of grid cells produce lower raster data resolution and vice versa. Theoretically, the size of grid cell can be chosen on any scale depending on the accuracy requirement and the capability of the hardware/software system. If the grid cell is small, a great number of grid cells is needed to represent a certain area. Then the consumption of computer resources is high in terms of space and time since computing time is proportional to the total number of grid cells (n). Thus the total number of nodes and links on the network models must be small, and the grid cell size must be greater than the minimum value as follows:

(31) $l_{min} = \sqrt{10^4 \cdot A/n_{max}}$

where l_{min} = minimum size of grid cells (m)
A = total area (ha)
n_{max} = maximum number of grid cells that is limited by computer hardware/software system

On the other hand, accuracy may be greatly reduced by choosing excessively large grid cells; e.g. every grid cell would be coded as a road if the grid cell size is equal to or greater than road spacing. Furthermore large grid cell sizes require much work in estimating raster data since several compartments may be located in a single cell. Therefore, the grid cell size must be smaller than a certain value. This value should not permit road cells to take up more than a half of the total grid cells (Nitami and Kobayashi 1992). Hence, the maximum grid cell size is determined by the following formula:

(32) $l_{max} = 5000/d_{max}$

where l_{max} = maximum grid cell size (m)
d_{max} = maximum road network density (m/ha)

Good raster data resolution must meet two requirements: accuracy (expression 32) and computer capacity (expression 31). In this study, the following approximate assumptions were made: $n_{max} = 1000$ nodes (according to the primary network routing model), $d_{max} = 20$ m/ha (about twice as much as the optimum road network density). Then expressions 31 and 32 for the 559 ha of the given planning area result in: $l_{min} = 75$ m, $l_{max} = 250$ m. Grid cell size covering an area of 100×100 m^2 (i.e. one hectare) was chosen since it is easy to use in calculations.

Finnish forest management planning documents are characterised by the feature that much information is presented for the basic units — compartments. A compartment is the smallest unit for which the forest stand properties are given. The information contained by a compartment is assumed to be homogeneous; i.e. there is no variation in the forest stand characteristics within a compartment. It is possible to formulate transportation networks on the basis of the compartment so that a compartment can be referred by its centre, which defines a node. This requires a complicated data handling system, and may need a vector database.

Since the raster database structure is used in the present study, a compartment-based data is also converted into raster data. When the size of compartments is greater than the size of grid cells, it is quicker to enter spatial data by the copying and replacing method as follows:

1) Create a compartment overlay by using a grid system. Each of the grid cells records the compartment number as its attribute and the coordinates as its spatial references. One compartment is registered in the data overlay by one or more grid cells depending on the size of compartment.
2) Make a copy of the compartment overlay.
3) Replace the compartment number (attribute), for each of the grid cells, with the real attribute (e.g. cost etc.) in that compartment.
4) Repeat steps 2 and 3 for every type of spatial data.

Only the first step requires digitising to get the attribute and coordinates for each of the grid cells. Digitising is not necessary in the following steps. The copying and replacing can also be done by a word processing program as long as it provides the replacing facility. However, copying and replacing are easy in the current digitising system. Instead of digitising all overlays, only one data overlay (compartment coding) is digitised and others are created by the copying and replacing method. This data entering method eases the task of entering data. In the example included in this study, the number of compartments (26) is less than the number of grid cells (559), and hence a great amount of work can be avoided by using the copying and replacing method. The compartments shown in the map in Fig. 15 (p. 42) were converted into digital form by raster mapping representation (Fig. 16). Two non-land cells were filtered out when the spatial data was transferred to the network routing system; thus, the total number of nodes used in the network routing system was only 557.

Most of the data overlays were encoded using their physical values (e.g. harvesting work in m^3/ha, silviculture work in mandays/ha). There are also some special codes for defining the nodes and links in the transportation networks. More details about the data overlays are given as follows.

1) *Transportation networks:* A separate data overlay was used to encode the transportation networks. The
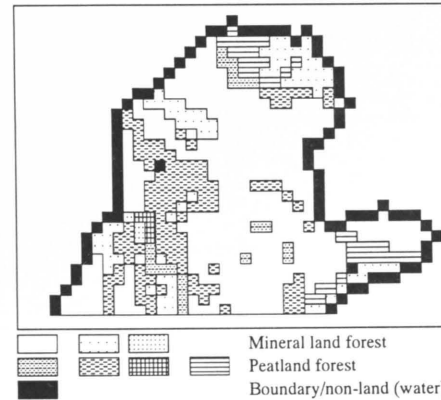

Fig. 16. Raster mapping of the compartments in the given road planning area.

codes for different types of land nodes (e.g. road, river, bridges) were the same as those listed in Fig. 8 (p. 26), and additional codes for boundaries and others were included as well. The spatial representation is shown in Fig. 39 (p. 83). More than one data overlays may be used if the structure of the area is complicated.

2) *Road cost:* The costs of road construction and road maintenance were entered simply into one data overlay (Fig. 40, p. 83), where the numeric value of cost was used for encoding. In addition, four directional data overlays were built because of the terrain restrictions (see the following text). It may be a necessity to use two or more data overlays depending on the method of road costing.

3) *Terrain transportation cost:* There are many factors which should be taken into account in terrain transportation costing. The costing method implied in the tariff schedule was used in this study. Terrain transportation includes both timber transportation and travel by the labour force. Altogether 6 data overlays were taken into the spatial database in relating to this costing. These overlays were: harvesting work in terms of cutting volumes (Fig. 41, p. 83), forest-related work other than harvesting in terms of man-days (Fig. 42, p. 83), terrain classes (Fig. 43, p. 84), harvesting methods (Fig. 44, p. 84), sawlog assortments, and pulpwood assortments. Most of these data overlays were encoded using their numeric values, except for wood assortments, which were encoded by their wood assortment composition in 1/10ths including logs and pulpwood for three species; i.e. Norway spruce, Scots pine and birch. The assortment overlays were not represented by raster

mapping because of their combined special codings whose meanings did not become clear in raster mapping.

4) *Road transportation cost:* The relevant factors contained in the data overlays for terrain transportation were also applied to wood transportation by road. In addition, the landing site class was assumed to be the same throughout the planning area. Travel by the labour force by road uses the same factors as those applied to travel by the labour force in the terrain but the means of travel were not included in the data overlays in which it was assumed that employers provide the transportation vehicles in road transportation and that workers move on foot to their work sites in the terrain.

5) *Directional coding:* There may be some broken terrain in the area, such as river, steep slope, or big rock, which represent extreme terrain restriction to transportation and road construction. Using some special codes could help the routing algorithm to process such extreme conditions. Four directional data overlays were used: west-east (Fig. 45, p. 84); southwest-northeast (Fig. 46, p. 84); south-north (Fig. 47, p. 85); and southeast-northwest (Fig. 48, p. 85). For complex terrain, more than one group of (four) directional overlays may be needed; e.g. one group for terrain transportation restrictions, and perhaps another group for extreme conditions for road construction. The directional data overlays are also useful in encoding lines or polygons such as road and river as shown in Figs. 45 to 48 in Appendix 4 (p. 84—85).

6) *Other coding:* Some non-forest use of the road system could be encoded separately of the above basic data overlays. However, such needs were not included in this study. Further investigations are necessary if these are to be taken into account.

It should be emphasised that encoding links crossing a polygon like a river by using the directional encoding method must be complete, since routing can be mislead to where a restricted link is missed. A simple and easy coding method is to assign all the links (eight as shown in Fig. 9, p. 26) around a river node with the code for river. A river link may be counted twice along one direction, which leads to a doubling of the price for bridge construction. For a better result, it is suggested that at first all the links crossing the river be drawn on paper and then digitising can be commenced based on this drawing. Fig. 17 illustrates the way how the river in the area of this study (Fig. 15, p. 42)
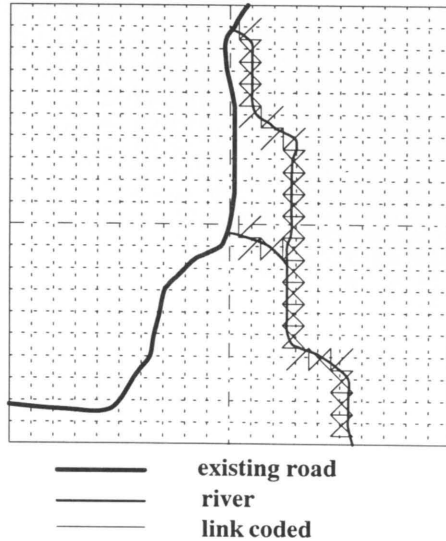
existing road

river

link coded

Fig. 17. Example of encoding the links when crossing a river.

was drafted onto a sheet of paper. A grid sheet is superimposed on the map sheet, and all the links crossing over the river are drawn using line segments. This drawing can be used for controlling and checking digitising. Of course, digitising may or may not be executed on this paper.

In summing up the above discussions, a total of 12 data overlays were used in the present study:

— land type codes;
— harvest volume in m^3/ha;
— cutting methods;
— other forest operation work in man-day/ha;
— terrain conditions;
— road costs;
— four overlays for directional codes (combined coding for both road construction and terrain transportation);
— sawlog assortments for spruce, pine and birch;
— pulpwood assortments for spruce, pine and birch.

The above list of data overlays is just an example; the flexibility depends on the user. Most of these data overlays were mapped in raster form through the spatial data handling

subsystem (Figs. 39 through 48 in Appendix 4). The number of data overlays needed depends on the complexity of both the terrain and the programs themselves. Spatial database management programs permit up to 20 data overlays to be taken into one file and each overlay can contain an area of up to 3 000 nodes. More than one file may be constructed if more than 20 data overlays are necessitated and each of the files can accommodate up to 20 data overlays.

The users' experience in this study was that a data overlay may take about 2 or 3 hours to be completed depending on the users' knowledge and skills in using the system. It took less than one manday of work to construct all 12 overlays and to complete the spatial database for the practical road planning problem included in the current study, since only one overlay (for compartments) was established using the digitising method; all the others were created from the structure of this compartment overlay using the copying and replacing method as mentioned in the beginning of this section.

4.2.4 Transportation route costing

Seven matrices were used to define the shortest paths for the three types of transportation networks. Two matrices were used for the path and cost of road construction network, two matrices for the path and distance of the road transportation network, and three matrices for the path, distance and average terrain class of the terrain transportation network. These shortest path matrices were not the same as those defined in the algorithms in chapter 3 (section 3.3.3, p. 28). The transportation route costing for road construction and maintenance, road transportation and terrain transportation was manipulated as follows.

The cost calculations were handled in a different way except for the road costs which were contained in the same shortest path matrices as defined earlier. The transportation costs were calculated as a function of distance and other factors from the tariff schedules as described in section 4.2.2 (p. 43). Three separate function procedures in the network routing system calculated the costs

for road transportation of wood, terrain transportation of wood and travel by the labour force. The costs of labour force travelling by road or on foot in the terrain were added into the corresponding costs of either road transportation or terrain transportation of wood. The tariff schedules use distance with intervals instead of a continuous variable. The cost value between the interval of adjacent distance classes was estimated by applying interpolation methods (Handbook of Mathematics 1979, see Appendix 2, p. 81).

Transportation networks were formulated as follows: the node attributes were entered by means of the spatial data handling system; the links were defined as connections between neighbouring nodes by using a separate subroutine (procedure DINFO as shown in Fig. 36, p. 76) in the network routing system by checking the neighbouring nodes and calculating the link lengths. The geometric length of a link was calculated as the straight line distance between two neighbouring nodes connected by the link (expression 7, p. 27). Link attribute, such as cost and average terrain class, was calculated as the average attribute value of two neighbouring nodes connected by the link (expression 8 or 9, p. 27).

To find all shortest paths between each pair of nodes, algorithm A1 in Appendix 1.3 (p. 77) was applied to road construction and road transportation. Since three matrices were used in the shortest path modelling for terrain transportation, algorithm A1 was further adapted as described further on.

The two main factors affecting the locations of wood terrain transportation routes were taken into the minimum distance routing model: travelling distance and terrain class. The cost per unit of transported wood was assumed to be a linear function of transportation distance under certain terrain conditions, expressed as follows:

(33) $C_{sw} = k_0 + k_t \cdot D_{sw}$

where C_{sw} = cost of terrain transportation of wood
D_{sw} = distance of terrain transportation of wood
k_0 = a constant representing fixed cost (e.g. terminal operations)
k_t = variable unit cost of wood transportation in terrain under terrain class t (t = 1, 2, 3, 4)

If there were different terrain conditions along the route, the average cost was calculated using the following formula:

(34) $C_{sw} = \dfrac{\sum_{t=1}^{4}[(k_0 + k_t \cdot D_{sw})D_t]}{\sum_{t=1}^{4} D_t} = k_0 + \sum_{t=1}^{4}(k_t \cdot D_t)$

where D_t = distance of terrain transportation under terrain class t
D_{sw} = total terrain transportation distance, and

$D_{sw} = \sum_{t=1}^{4} D_t$

It was found from an analysis of the tariff table (Puutavaran metsätraktorikuljetusmaksut 1988) that the following relationship applies concerning the unit costs between different terrain classes.

$k_2 = 1.20\,k_1$
$k_3 = 1.50\,k_1$
$k_4 = 2.00\,k_1$

where k_1, k_2, k_3, k_4 are the variable unit costs of timber transportation in terrain under terrain class 1, 2, 3, and 4

Let $f_1 = 1$, $f_2 = 1.2$, $f_3 = 1.5$, $f_4 = 2.0$, then expression 33 can be rewritten as follows:

(35) $C_{sw} = k_0 + k \sum_{t=1}^{4}(f_t \cdot D_t)$
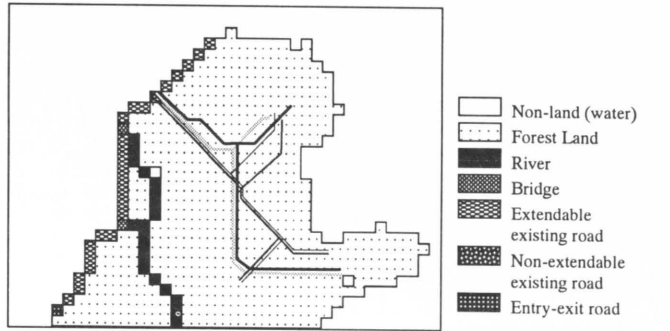
where $k = k_1$

The total cost of terrain transportation is minimised if the value of $\Sigma(f_t \cdot D_t)$ is at its minimum. Therefore, the routing rule used in this study has the following form:

(36) $\min_j \left(\sum_{t=1}^{4}(f_t \cdot D_t) \right)_j$

where j = alternative road routes

The shortest path matrix was obtained by applying the routing rule in expression 36. The factor f_t is a function of terrain classes. The average terrain class was applied and it was calculated using the following expression:

(37) $T = \dfrac{\sum_{t=1}^{4}(f_t \cdot D_t \cdot t)}{\sum_{t=1}^{4}(f_t \cdot D_t)}$

Legend:
- Non-land (water)
- Forest Land
- River
- Bridge
- Extendable existing road
- Non-extendable existing road
- Entry-exit road

Road network location index	ρ m	β m	d_r m/ha	D_s m	L_{er} m	C_{er} FIM	π FIM	References in the text
road-a1	∞	∞	9.1	295	3 461	121 429	274 675	§4.3.1
road-a2	150	∞	9.2	292	3 520	123 480	274 189	§4.3.2
road-a3	∞	900	8.9	286	3 387	120 143	282 375	§4.3.3
road-a4	150	900	9.4	270	3 628	128 592	282 222	§4.3.4

Fig. 18. Locations of the forest road network as found by the network routing system with the starting nodes of alternative A.

Legend:
- Non-land (water)
- Forest Land
- River
- Bridge
- Extendable existing road
- Non-extendable existing road
- Entry-exit road

Road network location index	ρ m	β m	d_r m/ha	D_s m	L_{er} m	C_{er} FIM	π FIM	References in the text
road-b1	∞	∞	9.8	293	3 887	168 454	236 421	§4.3.1
road-b2	150	∞	9.7	299	3 787	164 954	236 629	§4.3.2
road-b3	∞	1200	9.8	292	3 869	166 352	239 447	§4.3.3
road-b4	150	1200	9.8	292	3 869	166 352	239 447	§4.3.4 & 4.4.4

Fig. 19. Locations of the forest road network as found by the network routing system with the starting nodes of alternative B.

where T = average terrain class along the shortest route

The above manipulations were programmed into procedure SPMD in the network routing system (Fig. 36, p. 76) to find out the cheapest routes for terrain transportation by taking the two main factors into account. Then three shortest path matrices were determined to record the path, distance, and average terrain class.

4.3 Road locating case study results

4.3.1 Primary road locating outcome

The network routing system was applied in the selected planning area to find out the most economic location of the forest road network. As stated earlier, the target in locating a forest road network by means of the network routing system was to minimise the total cost of terrain transportation, road transportation, road construction and maintenance. In approaching this target, the searching procedure in the greedy-heuristic algorithm finds out the road route which reduces the total cost by the greatest amount interation by interation. The reduced total cost is called the net benefit induced from locating a road. The locations of a forest road network are then evaluated on the basis of the induced total net benefits. It was also stated earlier that the greedy-heuristic algorithm searches a relatively good location for a forest road network, which may not be the optimum solution. The network routing system is adapted to providing many alternative locations for a forest road network so that the final location of a road network could be the best solution from among all the alternatives.

By using different starting road nodes, for instance, several alternative locations of a forest road network were found out in the selected planing area. Of these alternatives, two relatively good solutions are shown as road-a1 in Fig. 18 and road-b1 in Fig. 19. In Fig. 18, all the nodes on the existing road were used as branching road nodes, which were the starting points for extending the current road network. In Fig. 19, some of the existing road nodes were coded as non-extendible road nodes, which prevented them from being connected to the new road. Each of the Figs. 18 and 19 also contains another three alternative solutions of the road network location; these are discussed in the subsequent sections. These two groups of alternatives are similar to the two proposals made by an experienced road planning expert and hence they are shown here for the sake of possible comparison between the algorithm's solutions and the expert's proposals; this matter is also discussed later at this chapter.

Some values in the optimum condition (i.e. marginal benefit being equal to marginal cost) of extending the forest road network for the selected planning area are presented in Figs. 18 and 19 in order to evaluate the alternative locations of the forest road network.

In calculating the road network density, the road on the boundary was counted for half of its length, since it should serve the forest areas on both sides of it and since one side is outside the selected planning area. The road network density in alternative road-a1 in Fig. 18 (i.e. 9.1 m/ha) is lower than that in alternative road-b1 in Fig. 19 (i.e. 9.8 m/h), but the average terrain transportation distance in alternative road-a1 in Fig. 18 (i.e. 295 m) is longer than that in alternative road-b1 in Fig. 19 (i.e. 293 m). These values illustrate the relationship between road network density and average terrain transportation distance. It was concluded that the alternative location road-a1 in Fig. 18 is better than road-b1 in Fig. 19 since the net benefit (FIM 274 675) of road-a1 in Fig. 18 is about FIM 38 254 greater than that (FIM 236 421) of road-b1 in Fig. 19.

In calculating these values, the money values were discounted into present values for the current year (i.e. 1988). Due to the nature of heuristics in the greedy-heuristic algorithm, it is suggested that more than one alternatives using different starting nodes be tested so that the best one might be found. Some other similar alternatives determined by modifications of the road locating procedure are presented in the subsequent sections.

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4.3.2 Using limited road extending reach

The principle of limited road extending reach was applied to the example in order to achieve short computing time by using the starting nodes of alternative A in Fig. 18. The result is presented as road-a2 in Fig. 18. The road extending reach for obtaining the alternative road-a2 in Fig. 18 is 150 m. This limited the routing procedure to include in set S′ only those positive land nodes as neighbouring nodes of the branching road nodes from set **B**, which allows the road network to be extended at each iteration for a distance of one grid cell only. There are differences between the results of road-a1 and road-a2 in Fig. 18. The total net benefit (FIM 274 189) calculated for road-a2, for example, is FIM 486 less than that (FIM 274 675) for road-a1; this may seem trivial, but the required computing time is significantly reduced — by about 80 percent under the conditions of the current case study.

Using the starting nodes of alternative B in Fig. 19 is an exceptional one in that the river bounds the branching road nodes since some nodes are coded as non-extendible. The limited road extending reach causes a termination of the road locating procedure when evaluating a road crossing a river. To prevent this interruption, the variable for the limited road extending reach was reassigned an infinite value. Once the road crossing over the river has been located, the road locating procedure is continued by using the limited road extending reach. The result of using the 150 m of road extending reach with the starting nodes of alternative B is presented as road-b2 in Fig. 19. There are also differences between the results of road-b1 and road-b2 in Fig. 19. The net benefit of road-b2, for example, is about FIM 200 greater than (instead of less than) that of road-b1, and the computation time required was half of that for obtaining road-b1.

The consumption of computing time depends on computer hardware and software environment and also on the method of transportation route costing. While the above figures concerning computing time are the results of the current case study, using a limited road extending reach could reduce computing time generally. In order to achieve the minimum computing time, it is suggested that the limited road extending reach be determined to extend a road network using a distance of one grid cell.

4.3.3 Solutions by bounded road catchment area

When a bounded road catchment area is used, the size of the bounded road catchment area has an important influence on the economic results of road locating. The size of the bounded road catchment area can be measured by its radius as it is circular in shape. An unbounded road catchment area may be regarded as being a special case of the bounded road catchment area: radius of the bounded road catchment area is between 0 and $+\infty$ in a length while an unbounded road catchment area takes the radius value of $+\infty$ (infinite) only. Different sizes of bounded road catchment area were applied to the example road-a1 using the starting nodes of alternative A in Fig. 18 in order to test their affects on the location of the road network. The variation in total net benefit according to the length of the radius of the bounded road catchment area is presented in Fig. 20. For the purpose of comparison with the results presented in the previous sections, the values in optimum condition in Fig. 20 and in the following examples, when applying the
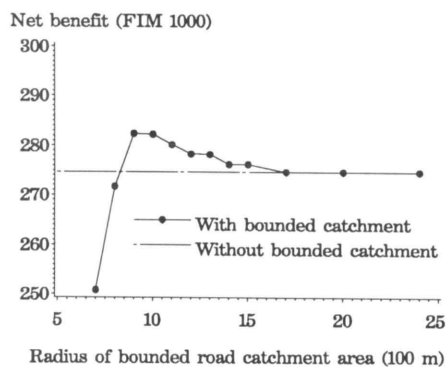

Fig. 20. Relationship between the total net benefit and the size of bounded road catchment area in the example road-a1 with the starting nodes of alternative A in Fig. 18.

bounded road catchment, were calculated for an unbounded road catchment area but the road locations were determined according to the principle of bounded road catchment area.

It is seen from Fig. 20 that total net benefit increases as the radius of the bounded road catchment area increases up to about 900 meters, at which point net benefit is at its maximum and then begins to decline. This declination stops at the radius length of about 1 700 meters. Thereafter, the net benefit does not change with further increase in the length of the radius of the bounded road catchment area. The general behaviour of the relationship between net benefit and the radius of bounded road catchment area may be described as increasing, decreasing and constant. There may be some variations if the conditions such as terrain and forest stand become very complex. The above described general behaviour is just an assumption rather than a model; further study is needed to test this hypothesis. The goal in using the bounded road catchment area was to find out a road network that results in the highest value for the net benefit. Road network location using a bounded road catchment area with a radius of 900 meters is presented as road-a3 in Fig. 18, where the total net benefit (FIM 282 375) is FIM 7 700 higher than that (FIM 274 675) of road-a1.

Further testing on the use of the bounded road catchment area was done in the example of road-b1 (Fig. 19) using the starting nodes of alternative B, where a river is encountered on the route of the road being extended. The variation in total net benefit with the length of the radius of the bounded road catchment area is presented in Fig. 21. When the bounded road catchment area is small, the marginal benefit (calculated within the bounded road catchment area) is also small. If the bounded road catchment area is too small, the marginal benefit may not be big enough to cover the marginal cost. Particularly when extreme terrain is encountered along the route of the road, the road-induced cost is very high as in the current example. In this case, the small bounded road catchment area results in no road route being feasible and hence road extending does not cross over extreme terrain. The road
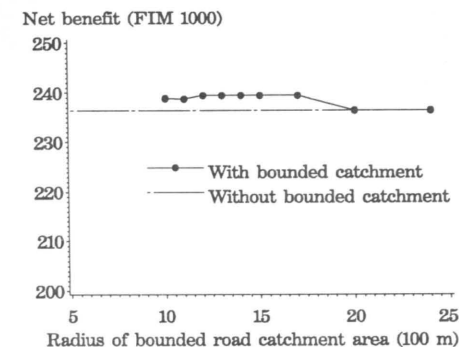

Fig. 21. Relationship between the total net benefit and the size of bounded road catchment area in the example road-b1 with the starting nodes of alternative B in Fig. 19.

could be extended over the river only if the radius of the bounded road catchment area was over one kilometre in length in the case of road-b1 using the starting nodes of alternative B in Fig. 21. With extreme terrain conditions such as a river, care must be taken when using a bounded road catchment area. Its size should be properly determined so that the river can be crossed.

The relationship in Fig. 21 between net benefit and the length of the radius of the road catchment area is similar to that in Fig. 20, but the increasing process is very brief and the peak value occurs within a range of about 1 200 to 1 700 meters; above this range the net benefit is constant. At maximum total net benefit, the road network is located along the same route, although greedy-heuristic road locating may take a different number of iterations and although the radius of road catchment area differs from 1 200 to 1 700 meters. The road network location giving the maximum net benefit is shown as road-b3 in Fig. 19, where the maximum net benefit (FIM 239 447) is about FIM 3 026 higher than that (FIM 236 421) of road-b1.

From the above results, it can be concluded that the use of a bounded road catchment area improves the economic outcome of the road locating as long as the size of the bounded road catchment area is properly determined. Based on the experience of this study, it is suggested that the

size of a bounded road catchment area should be about 2/3 of the road spacing or 3 times of the average terrain transportation distance as calculated using the optimum road spacing model (e.g. Matthews 1942, Larsson 1959, Sundberg and Silversides 1988) as follows:

$$(38) \quad \beta \approx \frac{2}{3} \cdot \sqrt{\frac{k \cdot C_r}{Q \cdot C_s}}$$

where β = radius of bounded road catchment area
C_r = cost of road construction
C_s = cost of forest terrain transportation
Q = quantity of timber production
k = a constant

4.3.4 Applying local network routing model

The method involving the local network routing model (section 3.4.3, p. 38) was tested with the example road-a1 using the starting nodes of alternative A in Fig. 18. The road extending reach and radius of bounded road catchment area were determined as being 150 m and 900 m respectively; these were considered to be the best combination. The size of the neighbourhood region was determined as $m_{br} = 1\,000$ m or $M_{br} = 10$ in raster coordinate units. The total number of nodes in a neighbourhood region was $n_m = (2M_{br}+1)^2 = 441$.

Using the same combination of road extending reach and radius of bounded road catchment area, both primary and local network routing models were applied and exactly the same solution for the road network location was obtained as is shown for road-a4 in Fig. 18. However, the local network routing model is recommended in order to reduce the requirement of computer resources in terms of space and time, since the total number of nodes in a neighbourhood region (i.e. 441) was less than that for the whole area (i.e. 557). In the case of the example road-a4 in Fig. 18, the disk space occupied by the data from the local network routing model was about 25 % of that occupied by the data from the primary network routing model. The time saving achieved by the local network routing model comes from the use of limited road extending reach and bounded road catchment area;

otherwise, the difference in time consumption is very small.

The values for costs and benefits of the example road-a4 shown in Fig. 18 were calculated without a bounded road catchment area so as to enable them to be compared with earlier results. However, if the local network routing model is used, the values are calculated within a bounded road catchment area only.

With extreme terrain conditions such as a river in Fig. 19, the value for M_{br} has to be more than 10 for the river to be crossed and the total number of nodes in a neighbourhood region is close to or greater than that for the whole area. Thus, the shortest path model did not provide improvements and was not used.

In applying the local network routing model, the size of the neighbourhood region in relation to the whole area has to be considered first. The general requirement is to select a size for the neighbourhood region that is less than that for the whole area. Otherwise, the primary network routing model should be used. More testing of the capability of the local network routing model is given later in this chapter in connection with a problem involving a very large network (section 4.4.2, p. 56).

4.4 Special considerations on road locating

4.4.1 Restrictions by extreme terrain

The restrictions imposed by extreme terrain on routing procedures is interpreted in terms of costs, which are higher in extreme terrain conditions. If the cost of crossing extreme terrain is high, routing will avoid such terrain. In the shortest path model, it is apparent that high cost points are always by-passed. In the greedy-heuristic road locating procedure, a road route is evaluated by considering not only the cost of road construction but also the costs of terrain transportation and road transportation. The road route may be located over extreme terrain if desired.

A river or stream is considered to be a special case of extreme terrain conditions. Transportation is impossible over a river or stream unless a bridge is built. It is shown in

Fig. 19 (p. 51) that the road locating is capable of crossing a river or stream if the road route satisfies the condition of feasibility. The restriction imposed by a river on road locating is in that routing will avoid a river whenever possible, since extra structures are needed to cross it.

Two assumptions are made when dealing with river-related nodes and links:

1) A road should not be built between two river nodes.
2) At most two neighbouring road links can be joined to a river node.

It is evident that the above two assumptions are necessary in avoiding higher cost routes and in excluding some infeasible road routes.

The example in Fig. 19 (p. 51) is a special one in that there is already a road crossing the river within the area so that the area on the other side of the river has a connection with an entry node, and hence the costs of terrain transportation can be determined both before and after the road route crossing over river by the road locating procedure. If there is no existing road connecting the two sides of a river, the costs of terrain transportation on the other side of the river prior to road planning are unknown since that area is isolated by the river. The unknown terrain transportation costs on the isolated area are entered as being infinite in using the road locating procedure, and infinite terrain transportation costs are excluded from the calculation of the total cost of terrain transportation in evaluating road routes. In this case, the road locating could not cross the river. However, this problem could be solved if the maximum allowable cost or distance of terrain transportation was given. The term of the maximum allowable cost or distance of terrain transportation can be explained as follows: the cost or distance higher than this maximum allowable value makes timber production with this terrain transportation economically infeasible; otherwise, timber production would be economically feasible. The difference between the maximum allowable cost and the total transportation cost, calculated after a road route crosses the river, is considered as the benefit of evaluating the road route. The river could then be crossed if the route for a road crossing the river is found to be

feasible. After crossing the river, road locating could be continued normally until the optimum is reached. The maximum allowable cost or distance of terrain transportation can be determined by applying market prices or an empirical method, which requires further studies. In this study, the maximum allowable cost or distance of terrain transportation was assumed as a given value.

Fig. 22 is used to illustrate a method of locating a road for accessing an isolated forest area. Before building a bridge over the river between points b and c, access to node a is impossible due to the restriction imposed by the river. An infinite value for the terrain transportation cost is normally assigned for the nodes on the other side of the river. If the maximum allowable cost is used to replace the infinite value, the total cost of terrain transportation for the whole planning area can be determined to include the nodes on the other side of the river. Thereafter, a road between points b and c is presumed. Given the presumed road, the transportation from point a assumes the terrain transportation route from point a to point b and road transportation route from point b to points c, d, e and further on to the end users. It is possible to find out the total cost of transportation for the whole planning area both before and after the presumed road. The costs of road construction and bridge
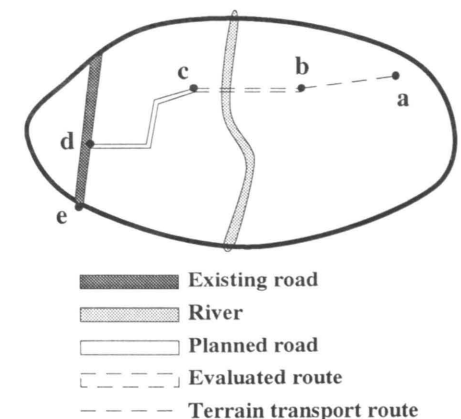

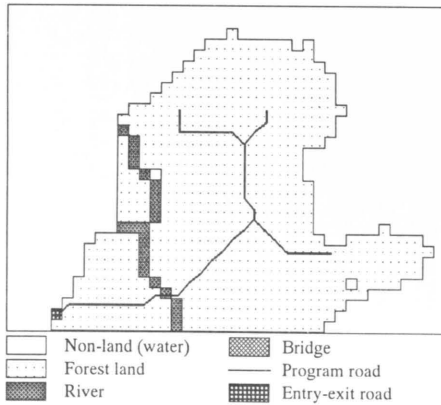Fig. 22. Thematic Illustration for accessing an area isolated by a river.

Fig. 23. Road network for accessing an area isolated by a river. $d_r = 8.9$ m/ha, $D_s = 288$ m, $L_{er} = 4\,956$ m, $C_{er} = $ FIM 204 495, $\pi = $ FIM 543 345.

construction between points b and c are determined as usual. In this way, it is possible to evaluate a road route accessing an isolated forest area.

By way of a demonstration, the example in Fig. 18 or 19 was modified by dropping out the existing road nodes except for entry node. In the example, there is an area isolated by a river. The initial terrain transportation costs for all the nodes on the other side of the river take the initial values as before. No further changes are necessary in the road locating procedure. The final results are presented in Fig. 23.

The net benefit in Fig. 23 was calculated using the assumed maximum allowable costs of terrain transportation for the nodes on the other side of the river. This value of net benefit is higher than the other alternatives in Figs. 18 and 19 due to the following reasons: 1) the existing road in Fig. 18 or 19 is located on the boundary of the given area and it is considered to be an inefficient location for this area (von Segebaden 1964) since only one side is used by the area; 2) the length of new road in Fig. 23 is greater than that in Fig. 18 or 19 since the greedy-heuristic road locating method accumulates greater benefit for longer roads.

4.4.2 Raster resolution affects

Raster resolution is a very important factor and it has to be taken into consideration. The higher resolution of raster data produces greater accuracy but requires more computer resources in capturing and handling data, and vice versa. With smaller sized grid cells, it is obvious that smaller spatial objects can be recorded into a spatial database whereas larger grid cells may result in loss of information. The size of the grid cells used depends on the study problem in question and the available computer system. A grid cell size of 100 m by 100 m, covering an area of one hectare, was used in the previous examples (section 4.2.3, p. 45). From the experience of program performance, this size was suitable for this case study. However, it is important to examine the results obtained using different grid cell sizes. Therefore, different grid cell sizes were applied in testing the road locating procedure in the example when using the starting nodes of alternative A in Fig. 18 (p. 50).

In order to retain most of the original spatial information, a higher resolution of raster data was used. The grid cell size was one half (i.e. 50 m by 50 m) of its former size, covering an area of 0.25 hectares. This resulted in a total of $557 \times 4 = 2\,228$ grid cells. Most of raster information was retained but some information in vector form had to be smoothed (e.g. the river and the road). After modifications, there were 2 205 nodes and 551.25 hectares left. All of the grid cells dropped out were those along the boundary of the area, where the existing road was located. The reasons for dropping out these nodes were that data processing is easier when the existing road route is smoothed, and the nodes on the boundary have little influence on the location of the road inside the planning area. The raster data overlays were the same as they were used earlier except for the existing road on the boundary (Fig. 24).

Given such a large number of nodes in a network and with the current computer software-hardware environments, the local network routing model had to be used since the primary network routing model for this very large network requires too much computer resources. As discussed in the
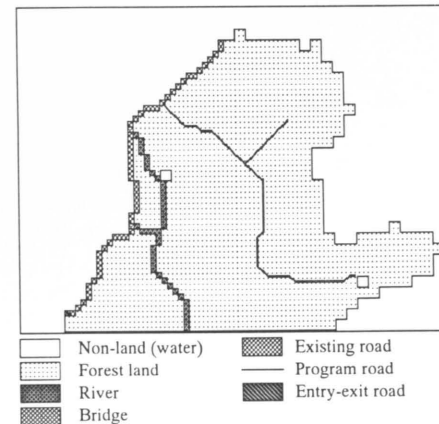

Fig. 24. Road network located by using raster size 50 m by 50 m and by local network routing model. $\beta = 900$ m, $\rho = 75$ m, $d_r = 9.2$ m/ha, $D_s = 284$ m, $L_{er} = 3\,556$ m, $C_{er} = $ FIM 126 184, $\pi = $ FIM 276 117.

previous sections, the best length of the radius for a bounded road catchment area is about 900 m, requiring 18 grid cells in the case of this large network. The neighbourhood region contained $37 \times 37 = 1\,369$ nodes. The limited road extending reach was set to 75 meters for extending the road by one grid cell distance at each iteration in accordance with a grid cell size of 50 m side length or 71 m when measured diagonally. The results are presented in Fig. 24.

The results in Fig. 24 are different from those in Fig. 18 (p. 50). The reasons are firstly due to the bounded road catchment area size. Since the change in grid cell size influences some spatial data in vector form (e.g. border and river alignments), the sizes of some catchment areas are also changed. On the other hand, although 900 m is specified, the smaller grid cell size may lead to different size of road catchment area as well. The difference in bounded road catchment area sizes could lead to differences in road network locations as discussed in the previous section concerning the bounded road catchment area (section 4.3.3, p. 52). Secondly, the shorter road extending reach (50 m or 71 m at each iteration) may change the influence of the ratio of benefit to cost. The example presented in this section is only

a demonstration, but it shows that higher resolution do not necessarily produce better road network location (when the results in Fig. 24 are compared with those in Fig. 18, p. 50) because of the above two reasons. The testing of the influence of raster resolution needs extensive further studies.

4.4.3 Computation times

In accounting for both the best economic location of a road network and the requirement of computing resources in using the road locating procedure, and although the net benefit is not the highest, the solution for road-a4 in Fig. 18 (p. 50) is considered to be the best when both bounded road catchment area and limited road extending reach are applied. In this case, the computing time was about 10 minutes once the shortest paths had been established. For obtaining the shortest path matrices, about 30 minutes of computing time were required. The shortest path matrices can be used repeatedly for obtaining other alternatives once they have been determined. The requirement on computing time depends very much on the hardware and software of the computer system, and on the size and characteristics of the planning area. The figures concerning computing times in this paper apply to the current study examples and the computer systems as mentioned earlier.
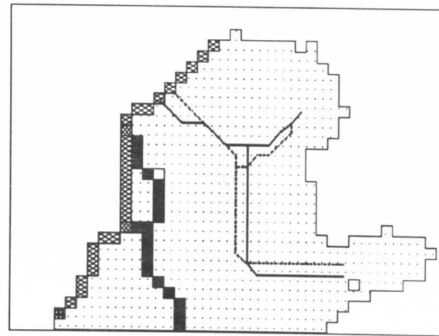
In general, the least computing time is required when the principles of both bounded road catchment area and limited road extending reach are used. The total time required in the case of obtaining the solution for road-a4 in Fig. 18, for example, without these two modifications may be 4 times higher than the least requirement with these two modifications embodied once the shortest paths have been established. Therefore, the bounded road catchment area and determined road extending reach are always recommended. When both of these modifications are applied, the local network routing model is more suitable for applying to larger areas, which consume the least computer resources in the terms of time and space. Particularly when the size of the network is very large, as in the example in section 4.4.2 (Fig. 24), it would not be possible to obtain

results without using the local network routing model. However, such a size of a network and neighbourhood region would not be considered to be practical given the current computer software and hardware system. To be appropriate, the neighbourhood region should be set to consist of about $31 \times 31 = 961$ nodes. If the grid cell is 100 m by 100 m, the radius of the road catchment area by this size of neighbourhood region would be 1 500 m, which normally meets most needs. Furthermore, the total area with these specifications can be up to 1 500 hectares in size.

4.4.4 Comparison with proposals made by experts

Experienced road planning personnel made two proposals for road network locations (dashed line in Figs. 25a and 25b) in the given forest area (Fig. 15, p. 42). These two proposals were processed by the network routing system so that the proposed road networks were optimised at the road endings. The optimisation at the road endings was made in order to equalise the road network density with the optimum road network density so that comparison could be made with the road network locations determined by the road locating procedure.

The first proposal (dashed line in Fig. 25a) is similar to the results presented in Fig. 18 (p. 50), and the second proposal (dashed line in Fig. 19, p. 51). These two groups of alternatives provided by the road locating procedure were apparently the results of two different sets of starting points. The highest net benefit from the first group of alternatives is road-a3 in Fig. 18 and that from the second group of alternatives is road-b3 in Fig. 19, when only the bounded road catchment area was used. However, considering both the best result and performance of the network routing system, the principles of both limited road extending reach and bounded road catchment area were used with these two different starting points to obtain results similar to proposals 1 and 2. The best combinations of determined road extending reach and radius length of bounded road

(a) β = 900 m, ρ = 150 m

(b) β = 1 200 m, ρ = 150 m

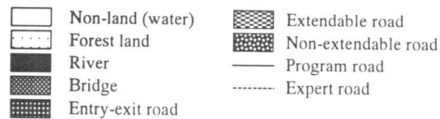|	
☐ Non-land (water)	▨ Extendable road
⠿ Forest land	▓ Non-extendable road
■ River	— Program road
▨ Bridge	---- Expert road
▦ Entry-exit road	
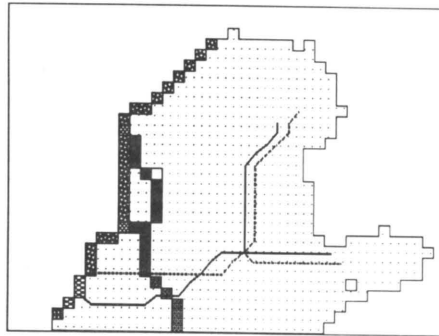
Fig. 25. The alternative forest road network locations proposed by road planning expert and those determined by the road locating procedure.

catchment area were: 900 meters and 150 meters (extending a road in length of 1 grid cell) respectively for the road network location similar to proposal 1 and 1 200 meters and 150 meters for the one similar to proposal 2. The results of both expert proposals and the road network locations by the road locating procedure were then plotted together (Fig. 25), and their optimum values are listed in Table 2. The alternative 1 in Table 2 refers to the road network locations in Fig. 25a and alternative 2 refers

Item Unit		d_r (m/ha)	D_s (m)	L_{er} (m)	C_{er} (FIM)	π (FIM)
Alternative 1 (Fig. 25a)	Expert	9.2	284	3 514	124 490	276 008
	Program	9.4	270	3 628	128 592	282 222
Alternative 2 (Fig. 25b)	Expert	9.9	277	3 931	184 403	225 836
	Program	9.8	292	3 869	166 352	239 447

to these locations in Fig. 25b, including the locations proposed by expert and the locations determined by the road locating procedure.

When comparing the net benefits calculated either in the two expert proposals or in the two road network locations achieved by the road locating procedure, the same conclusion can be drawn; namely that the first alternative in Fig. 25a is the better one since its net benefits (calculated for the expert proposal 1 and the first road network location by the road locating procedure) are higher. It is also evident that the road network locations determined by the road locating programs are as good as these proposed by experts when considering the net benefits derived in optimum conditions. The net benefits achieved in optimum conditions in the two road network locations determined by the road locating procedure (Fig. 25 and Table 2) are higher than the corresponding benefits calculated for the two expert proposals.

The spatial data handling-network routing system is not intended to replace the forest managers in making the decision concerning the road network location although it does provide better solutions under certain conditions. It should be only used as an aid for decision makers to approximate an optimum solution for a road network location. The user should be able to change the starting points for getting alternative results or to adjust certain routes for a better solution. Quantities similar to those in Table 2 could be obtained by using the programming system, which would be useful in determining the final road locations. However, the final route sitting depends on the actual terrain conditions and this has to be decided in connection with field work.

4.5 Selecting a forest road standard

The example of road-a4 using the starting nodes of alternative A in Fig. 18 (p. 50) is used to demonstrate the selection of a forest road standard. After the location of a forest road network has been determined, it is possible to select the desired forest road standard. The network routing system is mainly applied to calculating the flow quantity of timber or labour along each link of the road network, and this is one of the main factors influencing the selection of the road standard.

Timber flow depends on the road catchment area and the cutting volume. The road catchment area was determined by associating all the nodes in the planning area with their nearest road nodes. The formation of a road catchment area depends on the terrain transportation distances. Fig. 26a shows an isogram of terrain transportation distances calculated under the assumption that terrain transportation assumes bee-line transportation routes perpendicularly to roads. Such ideal terrain transportation routes were adapted to the real terrain variations and restrictions and were modified by the routes for the lowest terrain transportation costs. Fig. 26b illustrates an isogram of the terrain transportation distance using the cheapest routes. The road catchment area was generated by associating the forest land nodes with their nearest road nodes (i.e. terrain transportation costs from the forest land nodes to the road nodes were the lowest costs). Then the network routing system was applied to produce the road catchment area as shown in Fig. 27, which also shows the general direction of timber flows in the terrain and the quantity of timber delivered through each road link.

As mentioned earlier, the optimum loca-
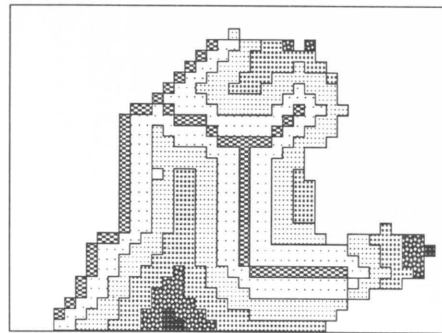
(a) Bee-line terrain transportation routes perpendicular to the nearest road
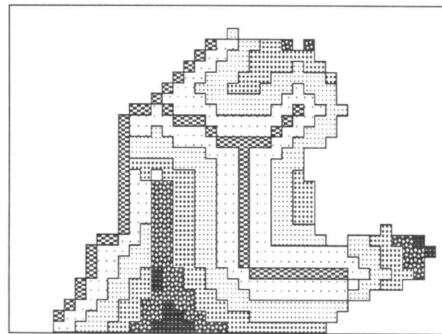
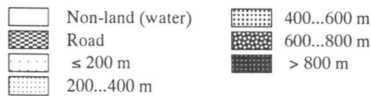(b) The cheapest terrain transportation routes

Non-land (water)	400...600 m
Road	600...800 m
≤ 200 m	> 800 m
200...400 m	

Fig. 26. Isogram map of terrain transportation distance.

Uncut area	1000...10 000 m³
Wood flow route	10 000...20 000 m³
≤ 1000 m³	> 20 000 m³

Fig. 27. Road catchment area, and timber flowing direction on terrain and quantity on road.

$$(39) \quad \delta = (C_{r2} - C_{r1}) + (2 \cdot C_{mt} \cdot Q_f / q_p)(V_1 - V_2)/(V_1 \cdot V_2)$$

where δ = difference between total costs of two road classes
C_{mt} = moving cost of vehicle per unit time
C_{r1} = road cost for quality alternative 1
C_{r2} = road cost for quality alternative 2
Q_f = timber flow quantities
q_p = payload of available vehicle
V_1 = desired vehicle velocity on road in quality alternative 1
V_2 = desired vehicle velocity on road in quality alternative 2

If the value δ is greater than zero, road quality class 2 would result in higher total costs and consequently road class 1 should be selected, and vice versa. The possibilities for selecting a higher road standard were checked for each link of the planned road network by using Expression 39.

Expression 39 is useful in evaluating the selection of a desired (higher) standard for an existing road. Decision making in road standard selection depends on the parameters in the expression 39, which can be demonstrated by Fig. 28. Fig. 28 is partly a numerical representation of the expression 39. The values of these parameters and categories were based on several sources; e.g. Metsäteiden rakentamista... (1988), Uusitalo

tion of a forest road network was determined for the lowest class of road standard. Once this has been done, the standard can be changed to a higher one if this is found to be economical.

In practice, the selection of road standards can consist of making the right choice between two different road quality classes. Such choice could be based on the total cost evaluation between the two different road quality classes. The difference in total cost between two different road quality classes can be calculated using the following expression:

q_l	m³	50											
C_{mt}	FIM/h	140				180				220			
V_1	km/h	20	20	20	20	20	20	20	20	20	20	20	20
V_2	km/h	30	40	50	60	30	40	50	60	30	40	50	60
$C_{r2} - C_{r1}$ (1000 FIM)		Minimum quantities of timber flow for selecting a better road standard (1000 m³)											
1		11	7	6	5	8	6	5	4	7	5	4	3
2		21	14	12	11	17	11	9	8	14	9	8	7
3		32	21	18	16	25	17	14	13	20	14	11	10
4		43	29	24	21	33	22	19	17	27	18	15	14
5		54	36	30	27	42	28	23	21	34	23	19	17
10		107	71	60	54	83	56	46	42	68	45	38	34
20		214	143	119	107	167	111	93	83	136	91	76	68
30		321	214	179	161	250	167	139	125	205	136	114	102
40		429	286	238	214	333	222	185	167	273	182	152	136
50		536	357	298	268	417	278	231	208	341	227	189	170

Fig. 28. Selecting forest road standards.

(1989), and Puutavaran autokuljetusmaksut (1988).

Let us take the choice between an area road and branch road as an example. The desired vehicle speed on branch forest roads is $V_1 = 20$ km/h, and that on area forest roads is $V_2 = 30$ km/h (Metsäteiden rakentamista... 1988). The cost of timber transportation per unit time for the truck type with full trailer with a payload of 50 m³ is assumed to be FIM 180/h (Puutavaran autokuljetusmaksut 1988). For that part of the roads in Fig. 27, which support timber flows of 10 000 to 20 000 m³, the selection of a higher standard is economical only if the cost difference of road construction between the two road quality classes (as indicated by speed V_1 and V_2) is less than FIM 2 000. Since the given planning area is small, the cost difference of road construction to select the higher standard between two road quality classes is restricted to be a low one. If the cost difference in selecting the higher standard between two road quality classes is not greater than that under the shaded dark area in the table of Fig. 28, the change from branch road to area road in the case of the example road-a4 in Fig. 27 is considered to be economical.

4.6 Sensitivity analysis

4.6.1 Variation of cost and benefit

Since the marginal cost and marginal benefit are used in evaluating a route for a forest road, the behaviour of the road locating procedure can be observed by investigating the variation in cost and benefit in extending a road network. With this purpose in mind, the routing process in the example road-a1 shown in Fig. 18 (p. 50) was continued after obtaining the optimum until the road length was extended to twice the length of the optimum. The results concerning the benefits and costs are presented in Figs. 29 to 31 and they are discussed as follows.

1) The total net benefit (Fig. 29) increases first with road network density, and then decreases after the peek value. This confirms the existence of an optimum road network density for a road network and proves the usefulness of searching optimum conditions.

2) Irregular fluctuation of the total net benefit with respect to road network density is shown in Fig. 29. This is further illustrated by marginal cost and benefit as shown in Fig. 30. This irregular fluctuation is the result of two main factors: terrain variation (as
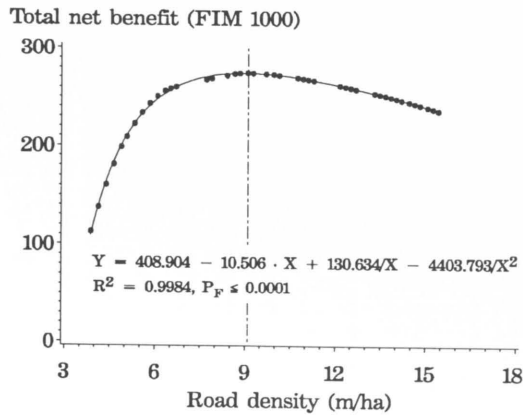
Total net benefit (FIM 1000)

$$Y = 408.904 - 10.506 \cdot X + 130.634/X - 4403.793/X^2$$
$$R^2 = 0.9984, \; P_F \le 0.0001$$

Fig. 29. Relationship between total net benefit and road density.

Marginal cost and benefit (FIM 1000)

1) $Y = 19.652 + 0.001 \cdot X$
   $R^2 = 0.0000, \; P_F \le 0.9856$
2) $Y = 16.170 - 279.638/X + 2940.538/X^2$
   $R^2 = 0.9894, \; P_F \le 0.0001$
3) $Y = -3.487 - 279.638/X + 2940.538/X^2$
   $R^2 = 0.9894, \; P_F \le 0.0001$

— 1 Cost
— 2 Benefit
— 3 Net benefit
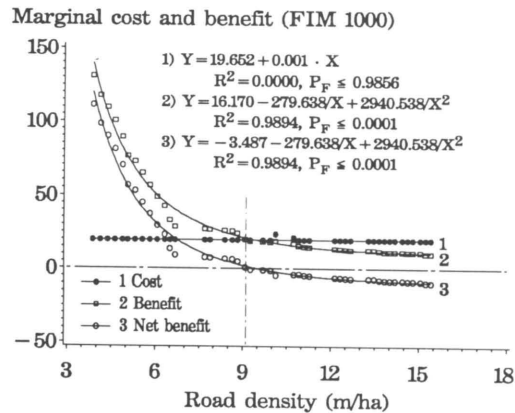
Fig. 30. Marginal cost and benefit as functions of road network density.

presented by the change of road cost in Fig. 30) and the change of road network structure which occurs at a new road branching point.

3) The marginal benefit decreases hyperbolically when the road network density increases with slight variation caused by changes in forest terrain and road network structure. The net marginal benefit decreases to a level below zero after the optimum road network density is reached. Meanwhile, marginal benefit is less than marginal cost. Further progression is considered to be infeasible. The marginal road cost is almost constant (with slight changes due to the terrain variation) as the road network density increases. No correlation was found to apply between marginal road cost and road network density, since $R^2 \approx 0$ in Fig. 30.

4) The total net benefit has a flat range around the optimum road network density, within which the rate of change of total net benefit is small (Fig. 29 and Fig. 31). Within the range of -20% to $+20\%$ of the road network density deviation around its optimum, the total net benefit decreases by less than 5% of its maximum value (Fig. 31). It seems that searching a range of road network density around the optimum is just as useful as, but more practical than, finding the exact point for the optimum road network density.

Road density (m/ha)
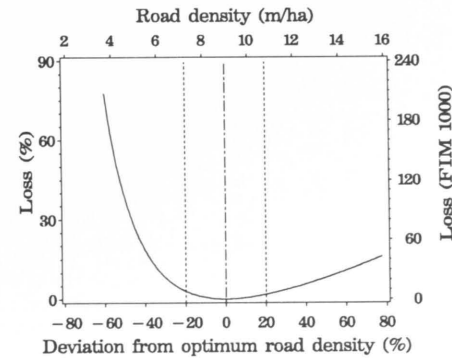
Fig. 31. Loss due to deviation of road network density from its optimum.

5) It is seen from Fig. 29 that the total net benefit has a higher rate of variation at lower road network density than that at greater road network density in relation to the optimum road network density. Therefore, an adequate forest road network is very important for obtaining the highest benefit. On the other hand, it can not be overlooked that over-construction of forest roads leads to losses in a long run. A lower road network density can always be increased by building more roads as needed, but the loss due to over-construction is irreversible and permanent. Therefore, forest roads should be built very close to optimum road network density but not exceeding it.

(a) Total net benefit (FIM 1000)

(b) Marginal cost and benefit (FIM 1000)
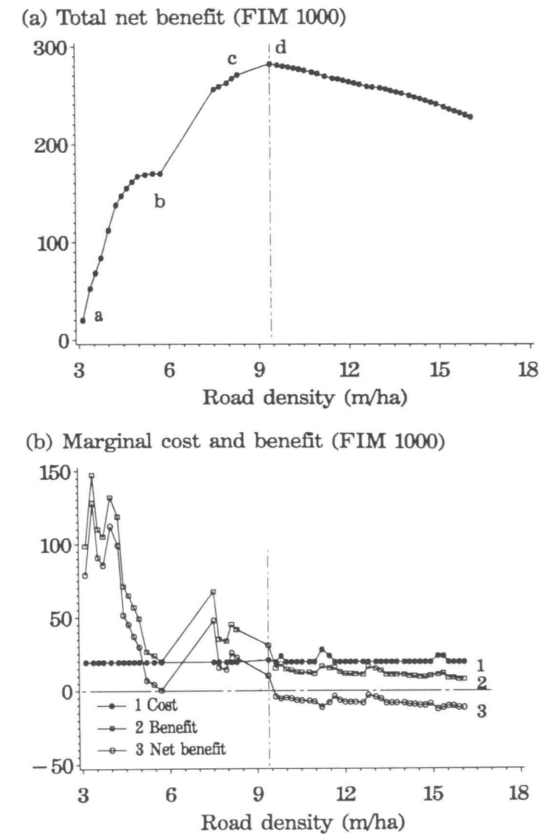

— 1 Cost
— 2 Benefit
— 3 Net benefit

Fig. 32. Variation in cost and benefit according to road density in extending the road network by using 150 m limited road extending reach and 900 m bounded road catchment area.

When the limited road extending reach and bounded road catchment area are used, the variation of cost and benefit as shown in Fig. 32 is coarser than that in the previous figures (Figs. 29 and 30). At certain places, the limitation on the road extending reach has to be ignored in order to select a feasible route crossing some extreme terrain. As a case in point, there are some jumps of net benefit at points like b and c in Fig. 32a, which are the result of ignoring the limitation on the road extending reach. The general trend in the variation in costs and benefits is similar to the results in the Figs. 29 and 30, although there are more irregular changes in the curves.

4.6.2 Effect of cost variables

Five cost variables were taken into account in locating a forest road network, including cost of road, costs of timber transportation in the terrain and by road, costs of travel by the labour force in the terrain and by road. Fig. 33 shows the variation in marginal values of these cost variables in extending the road network. The marginal costs of timber transportation in the terrain and travel by the labour force in the terrain are negative values, which are the components of marginal benefits in Fig. 30, while the costs of road construction and maintenance, timber trans-

portation on road and travel by the labour force by road are positive cost values, which are taken as the marginal costs in Fig. 30.

The magnitude of these marginal values reveals the extent of their influence on evaluating a forest road. It is apparent that the cost of road and cost of timber terrain transportation are the two significant variables. The influence of the other variables is very small due to the smallness of their marginal values as shown in Fig. 33.

The present values in considering the cost and benefit are simply used as constant costs and benefits in locating the forest road, but these values are time-dependent and thus vary with time. The influence of the variation in costs and benefits in road locating due to the time can be investigated by observing the variation of the optimum road network density and net benefit with the varying cost values for the following cost elements:

1) Cost of terrain transportation of timber.
2) Cost of road transportation of timber.
3) Cost of terrain travel by the labour force.
4) Cost of road travel by the labour force.
5) Cost of road construction and maintenance.
6) Cutting volume.

Cutting volume is one of the most important factors to be taken into account when conducting the activities for utilising the forest resources. Therefore, it was included in
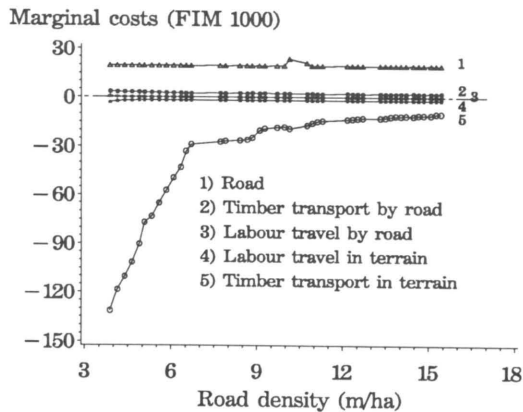
the analysis although many other costing variables are mathematical functions of it.

The variation of optimum road network density caused by changes in these cost elements is plotted in Fig. 34a. It is obvious that changes in optimum road network density are significant in relation to changes in cost of terrain transportation of timber. The higher the cost of terrain transportation of timber is, the greater the need for a forest road. A similar relationship exists between road network density and cutting volume; i.e. more forest road should be built when cutting volume increases and vice versa. On the other hand, when the cost of forest road

construction and maintenance is low, more forest roads are needed to balance the costs and benefits. Fig. 34a also indicates that the influence of other cost elements (e.g. timber transportation on road, labour travel both in terrain and by road) on optimum road network density is small.

The variation in road network density as affected by changes in cost elements is not smooth. This is because the road extending process is based on the ratio of benefit to cost. The behaviour of net benefit as influenced by cost element variation is much more regular and the same conclusions can be made as those applied to Fig. 34a. As a

Fig. 33. Influence of cost variables as indicated by their marginal values according to road network density.
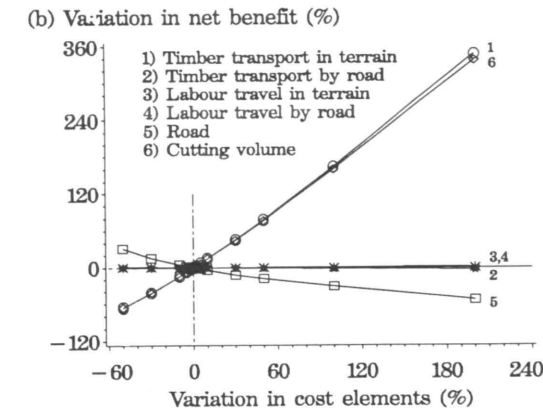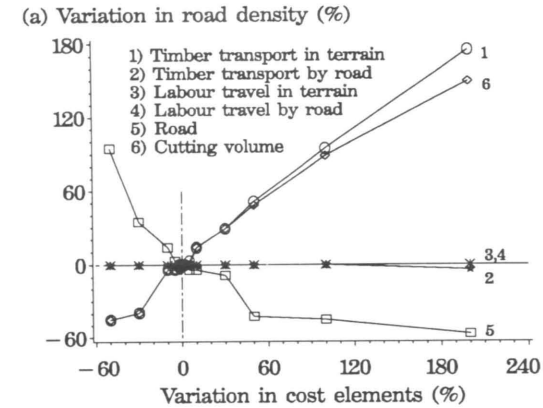

Fig. 34. Influence of changes in cost elements on (a) optimum road network density and (b) maximum net benefit.

reference to Fig. 34a, the variation in net benefit resulted in by the change in cost elements is plotted in Fig. 34b.

It is found in obtaining the results in Fig. 34 that the location of the road network has the same structure although the road network density or net benefit are changed by varying the cost elements. In other words, changes in cost elements caused by changes in the rate of inflation or interest, for example, can influence road network density, but the optimum location of the road network does not change except that part of the roads are removed or added. However, the above results based on the current study apply to just one case in practice. General application of these results requires extensive further studies.

4.6.3 Variation of spatial coefficients

The spatial coefficients change according to road network density as shown in Fig. 35; they are outputs at each iteration in locating the road-a1 in Fig. 18 (p. 50) by applying the road locating procedure. Using these spatial coefficients, it is possible to view the improvement of the road network provided by the road locating procedure.

The equality coefficient is big in the beginning of the routing process due to the existing road located on the boundary of the area. However, it decreases when the road network is extended and approaches the optimum road network density. It increases further after the optimum point because the roads are located closer to heavily forested stands and because the growing stands are not evenly distributed throughout the area.

The consistency and winding coefficients do not vary very much as the change in terrain conditions is only slight. The vicinity coefficient is below one and decreases all the time because the forest roads are located closer and closer to denser stands. This is why the overall spatial coefficient declines.

Fig. 35 shows that the spatial coefficients fluctuate with the extending of the forest road network. This fluctuation occurs when the road branches or turns to another direction; this is shown by Fig. 18. This is one of the reasons for the fluctuation in costs and benefits in Figs. 29 and 30 (p. 62).

4.7 Remarks on application

The first difficulty encountered in applying the current method into practices is how to get the necessary information together. Although forest management documents provide a lot of information, as in the case of the Finnish forestry practice, the costs related to road construction in various terrain conditions are not always readily

Fig. 35. Variation in spatial coefficients according to changes in road network density.

found and the costs of transportation both in terrain and by road are difficult to predict in the long term. However, forest managers need to be aware of all the costs no matter in what form and how roughly they are estimated, when planning a forest road network. This kind of cost information should be good enough for use in the current programming system. The estimation of the cost data must be done with great care and by experienced persons since the usefulness of the result provided by the system depends greatly on the reliability of the source data. In addition to all available information on documents and maps, further discussions with local foresters and visits to the field are essential.

The selected planning area is exceptional in that it is part of a state-owned forest estate. The road planning personnel are familiar with the timber harvesting and stand improvement plans. Timber harvesting and road building would be done soon after the road network planning is completed. The costs and benefits could be estimated using the current values for the year 1988 when the road network planning was made. The costing of terrain transportation and road transportation was estimated on the basis of the Finnish forest wage agreements. The cost of road construction and maintenance was estimated by the road planning experts who had experience of and had visited the planning area. All the affecting factors were taken from the aforementioned agreements. The activities of forest stand tending and so on were supposed to take place some time later, and their costs were discounted into present values by reducing the amount of work according to the discount rate. Since the cost of travel by the labour force have little influence on the location of forest road network, as was pointed out in section 4.6.2 (p. 64), the influence of the cost difference of the labour travel due to different interest rates is a minor one. The method of processing costs and benefits in the case of this study is most applicable when planning a forest road network on which the logging operations impose the greatest demands. In further applications, the costing factors may be varied and the raster data overlays used for mapping the cost elements may differ in definition and number, depending on the

actual environments. In private forests, logging operations do not take place at the same time for different owners, and the time factor (such as interest and inflation rates) should be taken into consideration when estimating costs. Section 4.6.2 (p. 64) shows that a change in cost elements mainly affects the value of the road network density, but it has little influence on the location of the road network. Since the emphasises in this study is on the methodological issues rather than on finding the real values, further studies are needed to take into account the time factor.

The minimum cost routing method may be summarised as covering the following three types: i) finding the shortest route by minimum cost; ii) finding the shortest route by minimum distance and then calculating the cost as a function of distance; iii) determining the weighted shortest route. All these three types of routing are possible when using the current system. Normally, the computing time required is the shortest for the first and the longest for the third. The choice in using these types of costing method is entirely up to the user, and the flexibility for changing the costing functions is also retained by the user.

In the case study, the grid cell size was set to be 100 m by 100 m; i.e. one hectare. Based on the experiences gained from this study, the 1-hectare grid system is applicable in most cases, but other sizes are also permitted by the current system as demonstrated in section 4.4.2 (p. 56). The road network routing procedures permit up to 1 000 nodes using the primary network routing model, and more nodes are made possible when using the local network routing model; perhaps as many as 1 500 or more nodes for the computer environments in this study. The bounded road catchment area and the limited road extending reach should be used when the local network routing model is applied. It is recommended that the local network routing model should use $31 \times 31 = 961$ nodes in the neighbourhood region, which has an area with a radius of 1 500 m around a node when the grid cell is 1-hectare in size. The radius for the bounded road catchment area is suggested to be about 2/3 of the road spacing or 3 times of the average terrain transportation distance at the op-
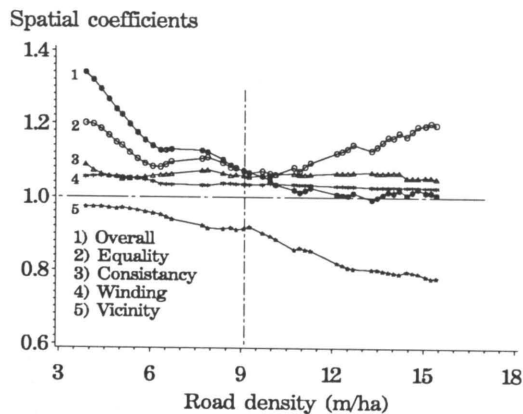
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timum point as calculated by the optimum road spacing model (expression 38, p. 54). The speedy use of the road locating procedure is achieved by means of the limited road extending reach which allows road extending to neighbouring nodes only.

The road locating procedure provides an approximate optimum solution. When the greedy-heuristic road locating algorithm is applied, optimisation is done at iteration level of road extension, but final result from the whole road locating process is only an estimation of the optimum solution for locating a forest road network in the given planning area. Therefore, the solution of the road locating should not be used directly as the final decision made concerning road network planning. Foresters must use their own judgement when making the final decision. If the preliminary location obtained is not satisfactory, alternative road locations should be determined by different starting points or different size of bounded road catchment area.

Transportation along waterways and by railways is not included in the case study. If they have to be considered, special codings and designs are required. However, the road locating procedure is not intended for routing waterways or railways. These can be included only as exogenous cost parameters and as part of the transportation network in the sense of existing roads. The road locating

has no influence on transportation by waterways or by railways.

The forest road locating procedure is designed to provide economic locations for forest road networks, which are most applicable in relatively flat areas. In the cases of mountainous areas, more terrain restrictions may be encountered and the spatial data is more complex. It might be very time consuming to encode these restrictions.

The cost-benefit analysis of developing and applying the current system has not been done, but it becomes apparent from this study that the development of this kind of system for just one area is not economical. To be truly beneficial, this kind of system should be developed for a large company and applied to forest road network planning in many forest areas. Due to the capability of the spatial data handling-network routing system, a large area should be broken down into smaller ones according to the nature of the terrain and forest stand. Care should be taken in delineating the boundaries of the selected road planning area as these should make the area independent so that terrain transportation within the planning area should not influence, and itself not be influenced by, that of the surrounding forest areas. The local network routing model should be used when a problem of a large network is involved.

5 General conclusion

5.1 Summary and conclusions

This study is concerned with the planning of a forest road network mainly serving forest-related activities within a forest area. The objective in forest road network planning is set to minimise the total cost of terrain transportation, road transportation, road construction and maintenance by controlling the road location, road network density and road quality, as well as giving consideration to environmental aspects. Due to the complexity and changing nature of the forest environments, forest road network planning is usually carried out by experienced per-

sonnel who use rules of thumb, which are not considered to be optimisation methods. Many theoretical studies on determining road location, road network density and road quality have encountered difficulties in taking into account the spatial diversity of the forest terrain and forest stands. The purpose of this study was to develop and demonstrate a method which could be of assistance to forest managers in the planning of forest road networks by covering the spatial and economic analyses and the determination of the desired road network density, road location, and road standard with the objective of minimising the total

cost of terrain transportation, road transportation, road construction and maintenance.

The forest road network planning implies that network analysis techniques could be useful. On the other hand, the spatial characteristic of forest resource data suggests that some kind of spatial data handling method may also be necessary. Thus, operations research (OR) and geographic information systems (GIS) were reviewed in order to determine their applicability for solving problems encountered in planning a forest road network. It was found that some network analysis techniques are very useful in modelling transportation networks. Network analysis techniques can also be applied to modelling the spatial property of forest resource data needed in planning a forest road network. However, the road locating problem formulated in this study could not be solved by the available OR techniques. GIS techniques were found to be applicable in handling the spatial data on forest resources, but GIS systems are expensive with respect to just solving forest road network planning problems. Besides, the state of the art GIS systems have not been developed for forest road planning and they are complicated to use. Therefore, a spatial data handling-network routing system was developed, containing two subsystems: a spatial data handling system and a network routing system.

The spatial data handling subsystem may be considered as an application of GIS techniques. It is aimed to be a simple and easy system with just a few functions for processing the necessary spatial data. The spatial database in this study used the raster database management method as it is easy in terms of data storage, data manipulation, spatial analysis and simulation, and permits the use of relatively simple computer programs based on relatively cheap technology. A digitising method was used for entering the spatial data with primarily point editing being used, but it also provided a facility for easy conversion of vector polygon objects (e.g. rivers, roads, boundaries) and areas (e.g. forest compartments) to raster data. However, if a GIS is available in a forestry enterprise and if it can be adapted to provide the manipulation of the required spatial data,

the current study method can be integrated with it.

The forest road network planning procedures in the network routing subsystem are primarily designed to solve the transportation network problems and to locate forest roads. Besides, the optimum road network density is determined simultaneously during the road locating. Road locating stops once the optimum road network density is obtained. The desired road standard is selected after the forest road network is located. The followings are the main features of the network routing system:

1) To simplify modelling, costs were summarised into three parts: terrain transportation, road transportation and road construction (road maintenance included), for which three networks were constructed. The costs of terrain transportation, road transportation, road construction and maintenance were calculated along the cheapest routes, which were found by adapting a standard shortest path model. If the objective of road locating is to find out the road route with the minimum road construction cost between two points, a proper road location could be determined directly from the shortest path matrices of road construction.

2) In locating a forest road, the objective is usually not just to achieve the cheapest road construction. It is the minimising of the total cost of terrain transportation, road transportation, road construction and maintenance that is difficult when using conventional methods. Standard OR algorithms were not considered to be applicable. Exhaust-enumeration can come up with the solution but it becomes impossible when the size of the transportation networks is large. Therefore, a greedy-heuristic algorithm was developed to find an approximate optimum solution for locating a forest road network. The greedy-heuristic algorithm uses a searching rule based on either maximum benefit or maximum ratio of benefit to cost. The greedy-heuristic algorithm contains searching procedures which, at each searching iteration, find the best feasible road route. A feasible road route is defined as the route for which the cost of road construction is covered by the road-induced benefit. These searching procedures extend the forest road network by one best feasible road at one searching iteration and continue to move from one iteration to another to reduce the total cost of terrain transportation, road transportation, road construction and maintenance by the greatest amount at each iteration until no feasible road can be found.

3) To improve on the capability and efficiency of the network routing system, the bounded road catchment area and limited road extending reach were introduced and the local network routing model was developed. A bounded road catchment area is the area limited by the maximum terrain transportation distance from a road node. Then the road locating is concentrated on considering the terrain transportation within the bounded road catchment area, which avoids the influence of the terrain transportation far beyond the bounded road catchment area. The limited road extending reach restricts the road extending length without exceeding a certain value. The local shortest path model is meant to find the shortest routes within the neighbourhood region around a node. The neighbourhood region contains only a subset of the nodes in that network for the whole planning area. Thus, the requirements imposed on computer resources are lower in terms of space and time. When the local network routing model is used, the bounded road catchment area and limited road extending reach must be used as well. The capability of the network routing system combined with the use of local network routing model, bounded road catchment area and limited road extending reach, was enlarged. These modifications were made to fortify the use of the network routing system.

4) The network routing system was also extended to carry out spatial analysis with regard to terrain transportation and was applied to calculating the amount of timber flowing or labour force travelling along any part of the road network; this is useful information when selecting the desired road standard.

While most of the procedures are applications of existing knowledge to solve new problems, a few of them were specifically developed in the course of this study. The greedy-heuristic algorithm was implemented on the base of the shortest path network model, which automates the task of road locating, and is capable of taking the projected road across extreme terrain if it is economical. An important achievement was that the network routing system enables the forest managers to carry out the spatial analysis and sensitivity analysis. The most important development was the use of bounded road catchment area, limited road extending reach and local network routing model, which enhanced the use of the system.

To test the applicability and limitations, the spatial data handling-network routing system was applied to solving problems encountered in a practical forest road network planning project. It should be noticed that this study was concerned primarily with issues of methodology, rather than with the details of application. The case study is merely a demonstration. However, a few findings and remarks from the case study could be useful for further applications.

1) Estimations concerning the cost data must be done with great care and by experienced persons as the usefulness of the results provided by the system depends greatly on the reliability of the source data. In addition to all available information on documents and maps, further interviews with local foresters and visits to the field are very important.

2) The raster resolution must be determined carefully to avoid two extremes. Excessively large grid cells greatly reduce accuracy, and this may impede presentation of spatial data. Too small a grid cell size increases the number of nodes which in turn may exhaust the available computer resources. It was also demonstrated by the case study that high-resolution spatial data does not necessarily produce better results in road locating when using the greedy-heuristic algorithm. The grid cell size used in this study was 100×100 m^2 for ease of calculation and it was found to be satisfactory in most cases.

3) The spatial data overlays entered by the spatial data handling subsystem are not the final networks. Since many factors influence the costing of terrain transportation, road transportation and road construction, there may be more than one spatial data overlay for defining each of the networks. The number of overlays needed depends on the complexity of both the terrain and the programs themselves. Spatial data overlays should be structured for the same boundary and coordinates, so that the three networks are compatible.

4) The difference between the economical results obtained with and without the limited road extending reach was trivial, but the consumption of computer time was significantly reduced — by about 50 % to 80 %. The speediness of use of the road locating procedure was achieved by the limited road extending reach which allowed road extending to neighbouring nodes only.

5) The size of the bounded road catchment area in road locating by the greedy-heuristic algorithm influences the location of the road network. Proper use of the bounded road catchment area improves the results. It is suggested that the radius of the bounded road catchment area should be about 2/3 of the road

spacing or 3 times the average terrain transportation distance at the optimum point as calculated using the conventional optimum road spacing model.

6) The bounded road catchment area, limited road extending reach and local network routing model should be used in most cases. The recommended number of nodes in the neighbourhood region is $31 \times 31 = 961$ nodes.

7) The main factors influencing road locating were found to be terrain transportation cost and road construction cost. The influence of the costs of labour force travel and road transportation of timber was small.

8) In the network routing system, up to 1 000 nodes could be processed by the primary road locating model, and about 1 500 or more nodes by the local network routing model, given the computer systems of this study.

It was found that for any given road network location, many values about the road network and transportation could be obtained using the network routing system, such as the marginal costs of terrain transportation, road transportation, road construction and maintenance; terrain transportation distance; road network density and so on, could be calculated. These enable forest managers to carry out spatial analysis and economical analysis.

So far, the spatial data handling-network routing system has limitations in its application to field operations due to its computation requirement which means that a main frame computer with a certain physical memory is necessary. The cost-benefit analysis on developing and applying the current system has not been done. However, it becomes apparent from this study that the development of this kind of system for just one forest estate is not economical. It is recommended that this type of system should be developed within a large enterprise and be then applied to forest road network planning on many forest areas. Due to the capability of the spatial data handling-network routing system, a large area should be broken down into smaller ones according to the nature of the terrain and forest stand.

The road locating procedure provides an approximate optimum solution. Using the greedy-heuristic road locating algorithm, the optimisation is done at interation level of road extension. In most cases, the final

solutions in locating a forest road network by the current system are, in term of cost and benefit, similar to those based on expert proposals. The final solution provided by the entire road locating process is only an estimation of the optimum location for the road network in the given planning area. Therefore, the solution of the road locating should not be directly used as the final decision made in road network planning. Foresters must base their decision on their own judgement. If the preliminary location is found to be unsatisfactory, alternative road locations using different starting point or different size of bounded road catchment area should be determined.

5.2 Suggestions for further research

This study has been arranged so that the fundamental methodology presented in chapter 3 constitutes the general infrastructure for the spatial data handling-network routing system and its application and adaptation to practical problems are retained their flexibility in order to be able to meet the constantly changing forest environments. Therefore, continuous development is inevitable. In addition, the spatial data handling-network routing system developed in the present study is a prototype. Further improvements are necessary for its use in practice.

To facilitate application within a relatively stable environment, a standardised method for costing terrain transportation, road transportation, road construction and maintenance could make it a routine to use this system; i.e. the system could be made applicable in many cases of forest road network planning. It is also necessary to extend the study to cover broader forest-related activities and the other uses of road networks. Should transportation on waterways and by railways be seen as being part of the transportation system, additional study is needed to encode their influence on transportation costing and road locating. In the case of mountainous areas, further studies are needed to cover complex terrain restrictions. A vector database such as that used by Sakai (1984) may be of more interest.

A very beneficial improvement would be due to reduction in computation time of the

network routing system. Most of the computations are spent on cost calculations, which could be speeded up by some skilful programming. The speed of determining the shortest routes by standard shortest path models may not be increased by a great extent, but there is a potential to make the system faster by improving the road locating procedure. For the use of road quality design in real life, the programs should be further improved to cover broader conditions.

Even beneficial would be to incorporate the system for forest road network planning with other forest resource management systems or harvesting analysis systems. Such systems are found from the literature; e.g. Herrington and Koten (1985), Reisinger and Davis (1986), Twito et al. (1987a), Covington et al. (1988), Covington et al. (1989), Wood et al. (1989a, b), Poso et al. (1990). Most of

them are capable of handling spatial data and some of them are integrated with some OR techniques. It would be useful for the network routing procedures to be integrated with these types of systems. It is of important to solve the problem of locating a forest road network for a forest area where forest stands have different harvesting schedules.

The most beneficial improvement would be to develop a user-interactive and integrated system, where the road locating procedure can be used for drawing the road network and the users are allowed to make changes to the network thus designed, and then obtain the economical parameters. It should also permit the users to draw their own road network designs and calculate the cost and benefit and facilitate the spatial and sensitivity analysis.

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Total of 117 references

Appendix 1. Algorithms

1.1 Procedures in the network routing system

The following figure (Fig. 36) shows the functional flow chart of the procedures in the network routing system. A brief description of the procedures is given in section 3.3.1 (p. 23).
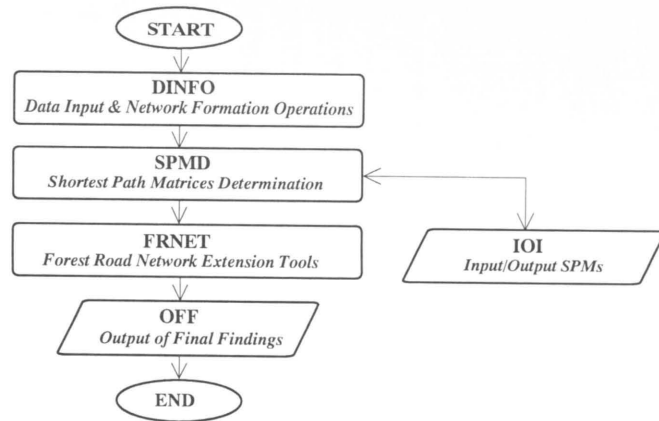
1.2 Outline of algorithms

The symbols in the following algorithms are defined in the text (chapter 3). The relations between the algorithms and procedures in the network routing system are shown in Fig. 37.

Fig. 36. Flow chart of procedures in network routing system.

Fig. 37. Outline of algorithms and relevant procedures.

1.3 Algorithm A1: shortest paths n × n

This algorithm finds the shortest paths between every pair of nodes in a connected network (section 3.3.3, p. 28). The number of paths to be found is n × n if n is the total number of nodes in the given network.

Step 1. Set i = 0

Step 2. Set i = i + 1

If i > n, go to step 8; otherwise, go to step 3

Step 3. If $l_{ii} = -\infty$, go to step 2; otherwise, for all $j \in N$, set

$p_{ij} = i$

$$c_{ij} = \begin{cases} 0, & \text{for } j = i \\ l_{ij} \cdot (z_i + z_j)/2, & \text{for } j \in E_i \\ \infty, & \text{otherwise} \end{cases}$$

and set $T = N - \{i\} - \{t | l_{tt} = -\infty\}$, where l_{ii} is the node code for transportation networks, then go to step 4

Step 4. Find a node k in T for which

$c_{ik} = \min_{j \in T} \{c_{ij}\}$

Step 5. Set $T = T - \{k\}$

If $T = \Phi$, go to step 2; otherwise, go to step 6

Step 6. For each $j \in T$, if $c_{ij} > c_{ik} + l_{kj} \cdot (z_k + z_j)/2$, then set

$c_{ij} = c_{ik} + l_{kj} \cdot (z_k + z_j)/2$

$p_{ij} = k$

Step 7. Go to step 4

Step 8. Stop. The shortest paths between all pairs of nodes are found. (Output P and C).

1.4 Algorithm A2: shortest paths 1 × n

This algorithm finds the shortest paths from a source node to all other nodes in a connected non-directed network (section 3.3.3, p. 28). The number of paths to be found is 1 × n if n is the total number of nodes in the given network.

Step 1. For all $j \in N$, set

$p_{ij} = i$

$$c_{ij} = \begin{cases} 0, & \text{for } j = i \\ l_{ij} \cdot (z_i + z_j)/2, & \text{for } j \in E_i \\ \infty, & \text{otherwise} \end{cases}$$

and set $T = N - \{i\}$

Step 2. Find a node k in T for which

$c_{ik} = \min_{j \in T} \{c_{ij}\}$

Step 3. Set $T = T - \{k\}$

If $T = \Phi$, go to step 6; otherwise, go to step 4

Step 4. For each $j \in T$, if $c_{ij} > c_{ik} + l_{kj} \cdot (z_k + z_j)/2$, then set

$c_{ij} = c_{ik} + l_{kj} \cdot (z_k + z_j)/2$

$p_{ij} = k$

find the first node u_1 after node i on the path from node i to j, then set $p_{ji} = u_1$

Step 5. Go to step 2

Step 6. Stop. The shortest paths from origin node i to all other nodes are found. (Output P and C).

1.5 Algorithm A3: primary road locating

This is the primary greedy-heuristic road locating algorithm (section 3.3.4, p. 29). The shortest path matrices CR, CS, CH, PR, PS, PH must be initialised in advance by algorithm A1 (Appendix 1.3).

STEP 1. Initialisation.

Step 1.1. Set

R = {i | i is a road node in the beginning; it may be an existing road, road structure or entries, $i \in N$}

O = {i | i is an entry node, $i \in N$}

S = {i | i is an initial positive land node, $i \in N$, $i \notin R$, and i is not a non-land node} where $S = N - R - \{$non-land nodes$\}$

B = {i | i is an initial branching road node and i has less than 4 branches, $B \subset R$}

Step 1.2. For all $i \in N$, set: $ct_i = \infty$, $rt_i = 0$, $ot_i = 0$

Step 1.3. For all $i \in N$, find a node u in R and a node v in O such that:

$cs_{iu} + ch_{uv} + co_v = \min_{j \in R, k \in O} \{cs_{ij} + ch_{jk} + co_k\}$

set

$ct_i = cs_{iu} + ch_{uv} + co_v$

$rt_i = u$

$ot_i = v$

Step 1.4. Set

$$GCT = \sum_{i=1}^{n} ct_i$$

Step 1.5. Set $bs_i = \infty$, for all $i \in N$.

For each of the candidate nodes $i \in S$, find the nearest branching road node k, such that

$$cr_{ik} = \min_{j \in B} \{cr_{ij}\}.$$

Set $bs_i = k$

STEP 2. Identifying a feasible road route with a maximum ratio of benefit to cost.

Step 2.1. Set $\mu = 1$, $\pi = 0$, $S' = S$, $w = \infty$

Step 2.2. If $S' = \Phi$, then go to step 2.8 else go to step 2.3

Step 2.3. Take a node w' from **S'**, and set:

R' = {i | i is a node on the path in the matrix **PR** from node w' to its nearest branching road node $bs_{w'}$, $i \in S$, $w' \in S'$, $bs_{w'} \in B$, and $bs_{w'}$ is defined in array **BS**}

Step 2.4. For all $i \in N$, find a node u in **R'** and a node v in **O** such that:

$$cs_{iu} + ch_{uv} + co_v = \min_{j \in R', k \in O} \{cs_{ij} + ch_{jk} + co_k\}$$

if $ct_i > cs_{iu} + ch_{uv} + co_v$ then set:

$ct_i' = cs_{iu} + ch_{uv} + co_v$

otherwise set:

$ct_i' = ct_i$

Step 2.5. Set

$$GCT' = \sum_{i=1}^{n} ct_i'$$

$$\mu' = \frac{GCT - GCT'}{cr_{ij}}$$

$$\pi' = (GCT - GCT') - cr_{ij}$$

where $i = w'$ and $j = bs_{w'}$

Step 2.6. If $(\mu' > \mu)$ or $(\mu' = \mu$ and $\pi' > \pi)$ then set $\mu = \mu'$, $\pi = \pi'$, $w = w'$

Step 2.7. Set $S' = S' - \{w'\}$, go to step 2.2

Step 2.8. If $w \neq \infty$ then go to step 3; otherwise go to step 4

STEP 3. Updating.

Step 3.1. Set

R' = {i | i is a node on the path in the matrix **PR** from node w to its nearest branching road node $bs_w \in B$ as defined in array **BS**, $w \in S$ and $i \in S$}

Step 3.2. Set

R = R + R'

S = S − R'

B = B + R'

Step 3.3. Update the shortest path matrices for transportation by road; i.e. **CH** and **PH**. A directed network uses Algorithm A1 (Appendix 1.3) and a non-directed network uses Algorithm A2 (Appendix 1.4).

Step 3.4. For all $i \in N$, find a node u in **R'** and a node v in **O** such that:

$$cs_{iu} + ch_{uv} + co_v = \min_{j \in R', k \in O} \{cs_{ij} + ch_{jk} + co_k\}$$

if $ct_i > cs_{iu} + ch_{uv} + co_v$ then set:

$ct_i = cs_{iu} + ch_{uv} + co_v$

$rt_i = u$

$ot_i = v$

Step 3.5. Set

$$GCT = \sum_{i=1}^{n} ct_i$$

Step 3.6. Set $bs_i = \infty$, for all $i \in N$

For each of the candidate nodes $i \in S$, find the nearest branching road node k, such that

$$cr_{ik} = \min_{j \in B} \{cr_{ij}\}$$

Set $bs_i = k$

Step 3.7. Intermediate calculations and output

Step 3.8. Go to step 2.

STEP 4. Save the final results and exit.

Step 4.1. Output the final data about the best road network

Step 4.2. Exit the procedure.

1.6 Algorithm A4: shortest paths $n \times n_m$

This algorithm finds the shortest paths from each node to all the nodes in its neighbourhood region (section 3.4.3, p. 38). The number of paths to be found is $n \times n_m$ if n is the total number of nodes in the given network and n_m is the total number of nodes in a neighbourhood region.

Step 1. Set $i = 0$

Step 2. Set $i = i + 1$

If $i > n$, go to step 8; otherwise, go to step 3

Step 3. If $i \notin R$ and $i \notin S$, go to step 2; otherwise, for all $J \in M$, set

$p_{iJ} = J_0$

$$c_{iJ} = \begin{cases} 0, & \text{for } J = J_0 \\ l_{iu} \cdot (z_i + z_j)/2, & \text{for } u \in D_8, j = e_{iu} \in E_i \\ \infty, & \text{otherwise} \end{cases}$$

and set:

$$T = M - \{J_0\} - \{J | J \in M, h_{iJ} \notin R \text{ and } h_{iJ} \notin S\}$$

where $i = h_{iJ_0}$, $j = h_{iJ}$, $J_0 \in M$

go to step 4

Step 4. Find a node K in **T** for which

$$c_{iK} = \min_{J \in T} \{c_{iJ}\}$$

Step 5. Set $T = T - \{K\}$

If $T = \Phi$, go to step 2; otherwise, go to step 6

Step 6. For each $J \in T$,

if $c_{iJ} > c_{iK} + l_{ku} \cdot (z_k + z_j)/2$, then set

$c_{iJ} = c_{iK} + l_{ku} \cdot (z_k + z_j)/2$

$p_{iJ} = K$

where $k = h_{iK}$, $u \in D_8$, $e_{ku} = j = h_{iJ} \in N$ and $e_{ku} \in E_k$

Step 7. Go to step 4

Step 8. Stop. The shortest paths are found from each node to all the nodes in its neighbourhood region. (Output **P** and **C**).

1.7 Algorithm A5: local road locating

This is a modified greedy-heuristic road locating algorithm based on the local network routing model (section 3.4.3, p. 38). The steps in this algorithm correspond to those in the algorithm A3 (Appendix 1.5), but the modified steps are listed in italics here. The shortest path matrices **CR**, **CS**, **CH**, **PR**, **PS**, **PH** must be initialised in advance by algorithm A4 (Appendix 1.6).

STEP 1. Initialisation.

Step 1.1. Set

R = {i | i is a road node in the beginning, which may be existing road, road structure or entries, $i \in N$}

O = {i | i is an entry node, $i \in N$}

S = {i | i is an initial positive land node, $i \in N$, $i \notin R$, and i is not a non-land node} where $S = N - R - \{$non-land nodes$\}$

B = {i | i is an initial branching road node and i has less than 4 branches, $B \subset R$}

Step 1.2. For all $i \in N$, set: $ct_i = \infty$, $rt_i = 0$, $ot_i = 0$

Step 1.3. For all $i \in N$, find a node u in **R** and a node v in **O** such that:

$$cs_{iU} + ch_{uv} + co_v = \min_{j \in R, k \in O, l_{ij} \leq \beta} \{cs_{ij} + ch_{jk} + co_k\}$$

where $U \in M$, $u = h_{iU}$, $j = h_{iJ}$, $l_{iJ} = \sqrt{\xi_{iJ}^2 + \psi_{iJ}^2}$, (ξ_{iJ}, ψ_{iJ}) are regional coordinates of node $J \in M$ at node i, $0 \leq \beta < \infty$

set:

$ct_i = cs_{iU} + ch_{uv} + co_v$

$rt_i = u$

$ot_i = v$

Step 1.4. Set

$$GCT = \sum_{i=1}^{n} ct_i$$

Step 1.5. Set $bs_i = \infty$, for all $i \in N$

For each of the candidate nodes $i \in S$, find the nearest road node k, such that

$$cr_{iK} = \min_{J \in M} \{cr_{iJ}\}$$

where $K \in M$, $k = h_{iK} \in B$, $j = h_{iJ} \in B$

Set $bs_i = k$

STEP 2. Identifying a feasible road route with a maximum ratio of benefit to cost.

Step 2.1. Set $\mu = 1$, $\pi = 0$, $w = \infty$ and set

S' = {i | i ∈ S and $l_{ik} \leq \rho$}

where $k = bs_i \in B$, $l_{ik} = \sqrt{(x_i - x_{bs_i})^2 + (y_i - y_{bs_i})^2}$ and $0 \leq \rho < \infty$

Step 2.2. If $S' = \Phi$, then go to step 2.8 else go to step 2.3

Step 2.3. Take a node w' from **S'**, and set:

R' = {i | i is a node on the path in the matrix **PR** from node w' to its nearest branching road node $bs_w \in B$ as defined in array **BS**, $i \in S'$, $w' \in S'$}

Step 2.4. For all $i \in N$, find a node u in **R'** and a node v in **O** such that:

$$cs_{iU} + ch_{uv} + co_v = \min_{j \in R', k \in O, l_{ij} \leq \beta} \{cs_{ij} + ch_{jk} + co_k\}$$

where $U \in M$, $u = h_{iU}$, $j = h_{iJ}$, $l_{iJ} = \sqrt{\xi_{iJ}^2 + \psi_{iJ}^2}$, (ξ_{iJ}, ψ_{iJ}) are regional coordinates of node $J \in M$ at node i, $0 \leq \beta < \infty$

if $ct_i > cs_{iU} + ch_{uv} + co_v$ then set:

$ct_i' = cs_{iU} + ch_{uv} + co_v$

Step 2.5. Set

$$GCT' = \sum_{i=1}^{n} ct_i'$$

$$\mu' = \frac{GCT\text{-}GCT'}{cr_{iJ}}$$

$$\pi' = (GCT - GCT') - cr_{iJ}$$

where $i = w'$ and $h_{iJ} = bs_{w'}$, $J \in M$

Step 2.6. If $(\mu' > \mu)$ or $(\mu' = \mu$ and $\pi' > \pi)$ then
set $\mu = \mu'$, $\pi = \pi'$, $w = w'$

Step 2.7. Set $S' = S' - \{w'\}$, go to step 2.2

Step 2.8. If $w \neq \infty$ then go to step 3, otherwise go to step 4

STEP 3. Updating.

Step 3.1. Set

$R' = \{i \mid i$ is a node on the path in the matrix *PR* from node w to its nearest branching road node $bs_w \in S$ as defined in array *BS*, $w \in S$, $i \in S\}$

Step 3.2. Set

$R = R + R'$

$S = S - R'$

$B = B + R'$

Step 3.3. Update the shortest path matrices for hauling on road, i.e. *CH* and *PH*. A directed network uses Algorithm A4 (Appendix 1.6) and a non-directed network uses Algorithm A2 (Appendix 1.4).

Step 3.4. For all $i \in N$, find a node u in **R'** and a node v in **O** such that:

$$cs_{iU} + ch_{uv} + co_v = \min_{j \in R', k \in O, l_{iJ} \leq \beta} \{cs_{iJ} + ch_{jk} + co_k\}$$

where $U \in M$, $u = h_{iU}$, $j = h_{iJ}$, $l_{iJ} = \sqrt{\xi_{iJ}^2 + \psi_{iJ}^2}$, (ξ_{iJ}, ψ_{iJ}) are regional coordinates of node $J \in M$ at node i, $0 \leq \beta < \infty$

if $ct_i > cs_{iU} + ch_{uv} + co_v$ then set:

$ct_i = cs_{iU} + ch_{uv} + co_v$

$rt_i = u$

$ot_i = v$

Step 3.5. Set

$$GCT = \sum_{i=1}^{n} ct_i$$

Step 3.6. Set $bs_i = \infty$, for all $i \in N$

For each of the candidate nodes $i \in S$, find the nearest road node k, such that

$$cr_{iK} = \min_{J \in M} \{cr_{iJ}\}$$

where $K \in M$, $k = h_{iK} \in B$, $j = h_{iJ} \in B$

Set $bs_i = k$

Step 3.7. Intermediate calculations and output

Step 3.8. Go to step 2.

STEP 4. Save the final results and exit.

Step 4.1. Output the final data about the best road network

Step 4.2. Exit the procedure.

Appendix 2. Interpolation methods

2.1. One independent and three points

Lagrangian interpolation formula (Handbook of mathematics 1979) is used here. Let y_k $(k = 1, 2, 3, ..., K)$ be the known values on the K points x_k $(k = 1, 2, 3, ..., K)$ of a function with a single variable (i.e. $y = f(x)$); then the value on any point x within the interpolation area can be estimated by the following formula:

$$f(x) = \frac{(x - x_{k+1})(x - x_{k+2})}{(x_k - x_{k+1})(x_k - x_{k+2})} y_k$$

$$+ \frac{(x - x_k)(x - x_{k+2})}{(x_{k+1} - x_k)(x_{k+1} - x_{k+2})} y_{k+1}$$

$$+ \frac{(x - x_k)(x - x_{k+1})}{(x_{k+2} - x_k)(x_{k+2} - x_{k+1})} y_{k+2}$$

where (x_k, y_k), (x_{k+1}, y_{k+1}), (x_{k+2}, y_{k+2}), are the known three neighbouring points.

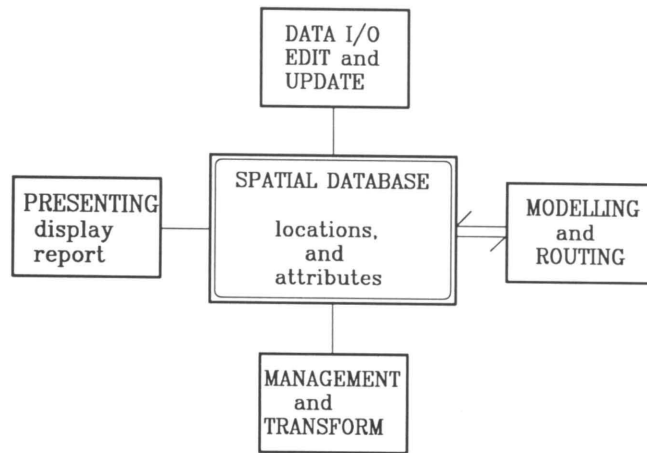### 2.2 Extension beyond the end points

Let y_0, y_1 be the two known values for a function with a single variable (i.e. $y = f(x)$) at the end point x_0 and the point x_1 next to x_0; then the value on any point x outside the end point x_0 can be estimated by the following linear equation:

$$f(x) = \frac{y_1 - y_0}{x_1 - x_0}(x - x_0) + y_0$$

Appendix 3. System configuration
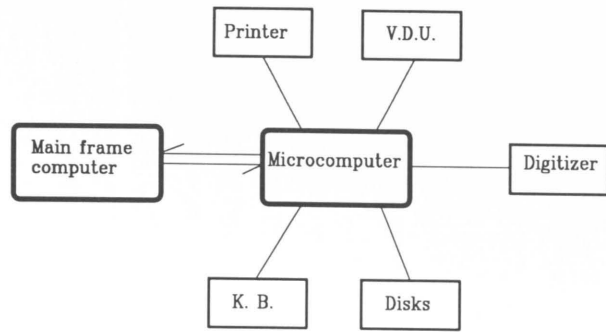
(1) Hardwares

(2) Softwares

Fig. 38. Configuration of computer hardware/software.

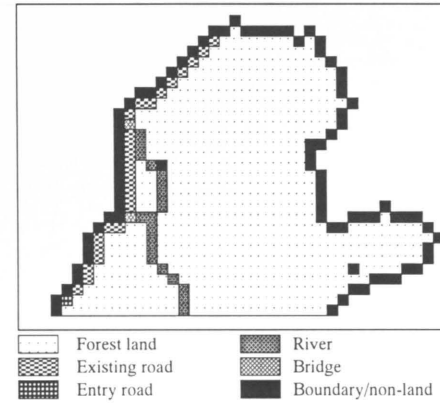## Appendix 4. Raster representation of the road planning data

Forest land		River	
Existing road		Bridge	
Entry road		Boundary/non-land	

Fig. 39. The forest land type in the given planning area.

≤ 35 FIM/m		> 50 FIM/m	
35...50 FIM/m		Boundary/non-land	

Fig. 40. Road cost.

≤ 50 m3/ha		Uncut
50...100 m^3/ha		Boundary/non-land
> 100 m^3/ha		

Fig. 41. Cutting volume.

No work		3 man-day/ha	
1 man-day/ha		≥ 4 man-day/ha	
2 man-day/ha		Boundary/non-land	
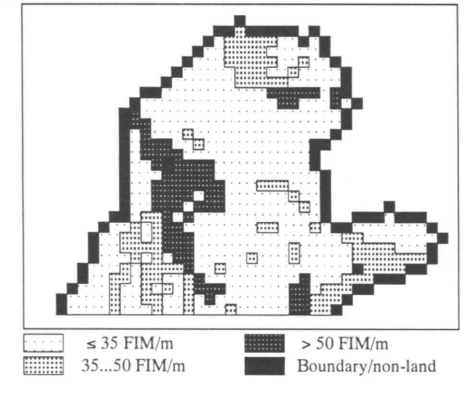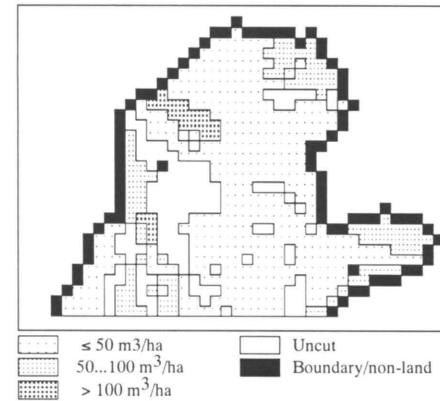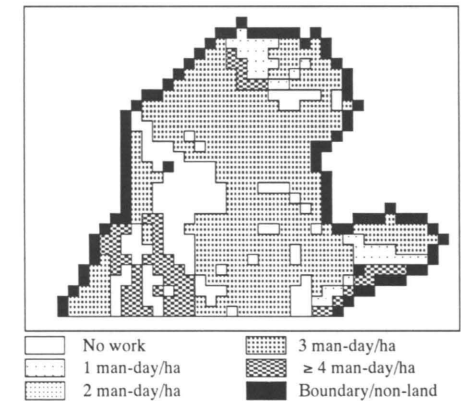
Fig. 42. Forest improvement work.
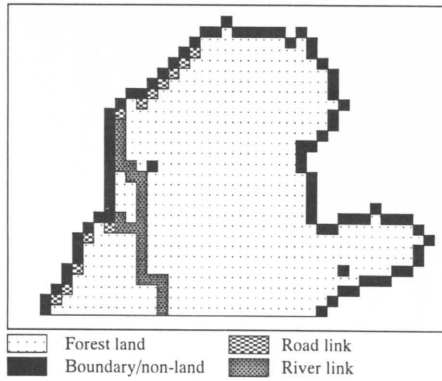
Fig. 43. The terrain condition coding.

Legend:
- Forest land
- Boundary/non-land
- Road link
- River link
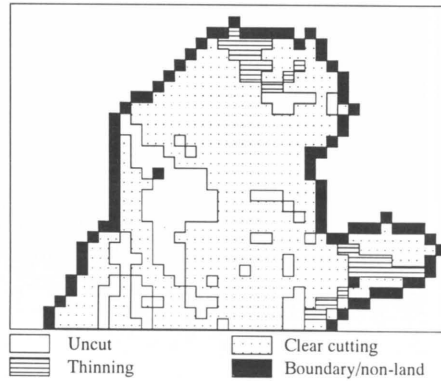
Fig. 44. The cutting method coding.

Legend:
- Uncut
- Thinning
- Clear cutting
- Boundary/non-land
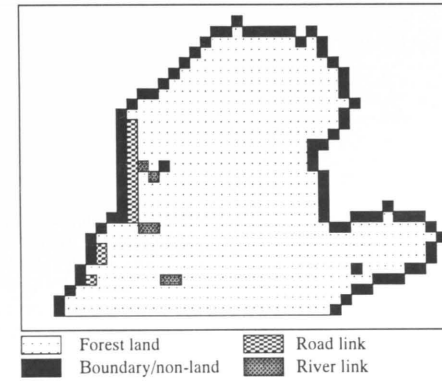
Fig. 47. The coded terrain restrictions in south-north direction.

Legend:
- Forest land
- Boundary/non-land
- Road link
- River link
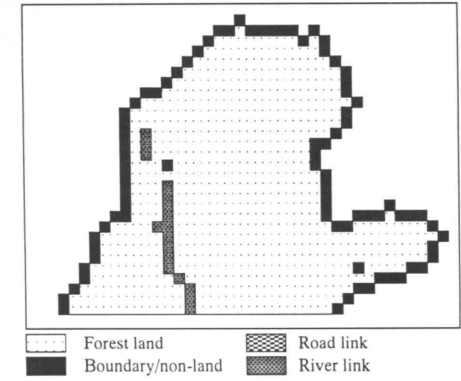
Fig. 48. The coded terrain restrictions in southeast-northwest direction.

Legend:
- Forest land
- Boundary/non-land
- Road link
- River link
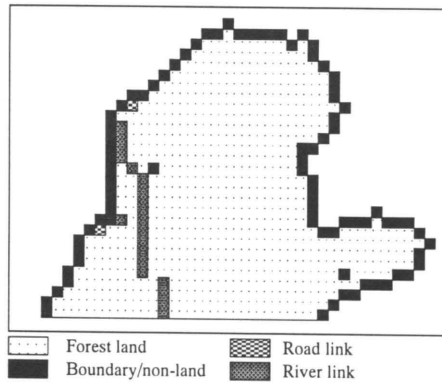
Fig. 45. The coded terrain restrictions in west-east direction.

Legend:
- Forest land
- Boundary/non-land
- Road link
- River link
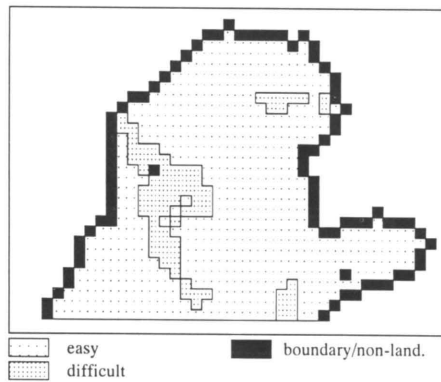
Fig. 46. The coded terrain restrictions in southwest-northeast direction.

Legend:
- easy
- difficult
- boundary/non-land.

Instructions to authors — Ohjeita kirjoittajille

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For matters of form and style, authors are referred to the full instructions available from the editors.

Käsikirjoitusten hyväksyminen

Metsäntutkimuslaitoksesta lähtöisin olevien käsikirjoitusten hyväksymismenettelystä on ohjeet Metsäntutkimuslaitoksen julkaisuohjesäännössä.

Muista käsikirjoituksista lähetetään Suomen Metsätieteellisen Seuran toimitukselle kolme täydellistä, viimeisteltyä kopiota, joihin sisältyvät myös kopiot kaikista kuvista ja taulukoista. Originaaliaineistoa ei tässä vaiheessa lähetetä.

Vastaava toimittaja lähettää käsikirjoituksen valitsemilleen ennakkotarkastajille. Tekijän on otettava huomioon ennakkotarkastajien ja toimituskunnan korjausesitykset. Korjaukset on tehtävä vuoden kuluessa siitä, kun käsikirjoitus on palautettu tekijälle. Jos tekijä ei voi hyväksyä korjausesityksiä, hänen on ilmoitettava eriävä mielipiteensä vastaavalle toimittajalle tai toimituskunnalle, joka tarvittaessa ottaa asian uudelleen käsittelyyn.

Acta Forestalia Fennican toimituskunta päättää kirjoituksen julkaisemisesta ennakkotarkastajien lausuntojen ja muiden ilmenneiden seikkojen perusteella. Päätös tehdään kolmen kuukauden kuluessa siitä, kun käsikirjoituksen lopullinen korjattu versio on saapunut toimitukselle.

Hyväksymisen jälkeen käsikirjoitukseen ei saa tehdä olennaisia muutoksia ilman vastaavan toimittajan lupaa. Suuret muutokset edellyttävät uutta hyväksymistä.

Tekijä vastaa kirjoituksen tieteellisestä asiasisällöstä ja kieliasusta. Tekijä ei saa julkaista kirjoitusta muualla ilman Acta Forestalia Fennican julkaisijoiden suostumusta. Acta Forestalia Fennicaan hyväksytään vain aiemmin julkaisemattomia kirjoituksia.

Tekijän tulee antaa lopullinen käsikirjoitus ja kuvaoriginaalit toimitukselle kahden kuukauden kuluessa hyväksymispäätöksestä. Käsikirjoituksen saatteesta pitää selvästi ilmetä, että käsikirjoitus on lopullinen, painoon tarkoitettu kappale. Teksti otetaan mieluiten vastaan mikrotietokoneen levykkeellä, jonka lisäksi tarvitaan paperituloste.

Käsikirjoitusten ulkoasu

Käsikirjoituksen asun tulee noudattaa sarjan kirjoitusohjeita, joita saa toimituksesta.

ACTA FORESTALIA FENNICA