Modeling and simulation of operational forest planning in relation to road network layout, cable corridor layout and timber transportation

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Introduction

1.1 Background

Forest management planning is regarded as a type of task with an extensive decision making component, requiring appropriate choice of forest management activities to satisfy the objectives of decision makers [10]. Use of optimization techniques is widely considered to be effective in this regard and have been applied to various types of forest management planning. Optimization techniques have been applied to diverse forest management planning. In the early stage of application, the 1960s and 1970s, a linear programming model was mainly used to address long–term forest planning over several decades, with the objective of maximization of present profit value or timber production volume [e.g., 76, 95]. However, a linear programming model does not deal with discrete options because the decision variables are continuous. This model is thus unsuitable for developing detailed plans required to perform actual forest management activities or for application in decision-making when spatial elements are concerned, for example, which forest stands should be harvested or where roads should be built. A later development is discrete/combinatorial optimization techniques (e.g., integer linear programming models) which allow addressing a higher level of problem complexity for real forest planning situations with discrete decision variables [e.g., 138, 150]. Because these techniques describe spatial restrictions and combinatorial structures inherent in forest management planning well [149], they encompass a broad range of applications. For the application of these techniques, see related reviews [8, 32, 151].

The levels of forest planning are classified in three categories according to the length of the planning horizon: strategic, tactical and operational level. On the operational level, plans of action of less than a year' duration are developed to determine how practical short–term forest management activities should be carried out [11]. As these plans require a high level of detail and contain many spatial elements, the application of discrete/combinatorial optimization techniques is highly appropriate at this level. Major operational forest planning problems include the following [42]: road construction; installation and use of harvest machinery; timber harvesting operations; timber transportation. Research attention should be focused on (*i*) formulation of operational forest planning problems and (*ii*) development of heuristic algorithms for the formulated problems. Decision makers who are actually dealing with problems (e.g., forest managers or engineers) have to be able to make rational decisions. Problem formulation is therefore necessary to make problems tractable both objectively and mathematically. On the other hand, it is important to develop high-performance heuristic algorithms, as it has been conjectured that due to problem size and combinatorial nature, there exist no efficient exact algorithms for operational forest planning problems.

1.2 Literature review

This section reviews the literature on the planning of forest road networks, timber harvesting operations, and timber transportation, areas that represent an important component of operational forest planning.

1.2.1 Optimal road spacing

In the classic book by Matthews [87], the following location problem of forest roads is discussed: Given undeveloped areas with uniform forest cover, on flat terrain, we have to locate optimal parallel roads to harvest the areas, use of ground-based skidding systems as harvesting machinery being assumed. The objective function is the sum of road construction costs and skidding costs, which are proportional to road construction length and skidding distance, respectively. The hypothetical condition (i.e., parallel roads, uniform forest and flat terrain) eliminates concrete spatial elements and transforms the nature of the problem from one of road location to one of most advantageous road spacing. A road spacing which minimizes the objective function is called *optimal road spacing* (ORS). To date, ORS under more practical and realistic conditions has been studied by adding various factors which affect ORS [e.g., 113, 117, 139]. ORS for cable yarding systems was also investigated by replacing skidding costs with yarding costs in the objective function [57, 68]. Whether harvesting machinery is composed of ground-based skidding or cable yarding systems, ORS has been shown to be an appropriate starting point for planning forest road networks. However, the information provided by ORS is quantitative, not qualitative, and contains no spatial detail. Thus, a different approach is necessary to design specific road networks.

1.2.2 Graph–theoretic approach

A graph-theoretic approach was introduced into forest road network design in the 1960s [77]. This approach focuses on the discrete, combinatorial nature of design processes and enables the determination of road spatial locations, e.g., the location of straight line segments, curved segments and junctions. In the following, a combinatorial optimization problem dealing with forest road network design is referred to as a *forest road network design problem* (FRND).

Given a graph representing an alternative (potential) network, a typical network design problem involves appropriately adding some edges of the graph to the solution, that is, determining an optimal subgraph of the graph subject to feasibility constraints [48]. In the case of FRND, which falls into the category of network design problems, the graph generally contains a potential road network with edges weighted by road construction costs; adding edges to a solution can be interpreted as a decision to construct road sections corresponding to the edges. Murray and Snyder [92] have pointed out that FRNDs are divided into two main problem domains. In one domain, where road construction decisions are often treated as part of harvest scheduling decisions [e.g., 93, 96, 104, 152], a single road section corresponding to an edge is composed of a number of straight line segments and curved segments, and is defined a priori by forest engineers. In the other domain, by contrast, it is composed of a few (often only one) straight line segment and/or curved segments, and the focus is not only on planning the overall layout of road networks, but also on designing road alignments incorporating some basic design elements such as horizontal curve radius or road gradient. Generally problems in the latter domain are at a more operational level compared to ones in the former domain, because of a shorter planning horizon and smaller road sections.

Hereafter, attention will be restricted to operational problems in the latter domain only.

The practical applicability of forest road network layouts designed by graph-theoretic approaches has been increasing in recent years for several reasons [127]: (1) the development of optimization techniques based on graph-theoretic approaches, (2) the increase in computer capabilities, and (3) increased accessibility of high resolution DEMs (digital elevation models) from LiDAR (light detection and ranging) data.

1.2.2.1 The multiple target access problem

An FRND involving decisions about road construction only is termed a *multiple target access problem* (MTA) [33]. In MTA, a forest engineer is given *targets*, which are places of destination (e.g., candidate landings) in forest areas, and *existing nodes*, which are places on an existing road network and from which new roads can be constructed, and then seeks to expand a road network from an one so as to provide access to the targets while employing minimum construction cost. Formally MTA can be stated as follows: Given a graph, a set of targets and a set of existing nodes, determine a minimum cost subgraph such that there is a path from one or more existing nodes to each target. Several heuristic algorithms for solving MTA have been proposed [e.g., 4, 33, 126]. Unfortunately, for forest engineers MTA features some deviation from practical tasks, as specific targets are rarely given as a precondition.

1.2.2.2 Forest road network design problem with timber harvesting operations

FRNDs different from MTAs usually involve decisions about both road construction and timber harvesting operations. As mentioned above, this type of FRND reproduces a practical and common task for forest engineers. Table 1.1 summarizes the literature related to this type of FRND. Informally, the problem can be described as follows: Assume that there is currently a set of timber resources to be harvested and that a forest engineer seeks to design a road network suitable for harvesting the timber resources by particular harvesting machinery. When modeling the problem on a graph, it is necessary to explicitly incorporate timber harvesting operations. Hence the graph contains both these and a potential road network. Timber harvesting operations, through which a timber resource is transported from its stump to the exit of the forest, are composed of multiple steps and work processes such as landing construction, harvesting machinery installation, skidding/yarding operations (off–road transportation to move timber from stump to roadside) and on–road transportation to the exit. As with road construction, these work processes (except on–road transportation) are represented as edges weighted with incurred cost in order to make them mathematically tractable. The decision to execute work processes is equivalent to the addition of the corresponding edges to a solution. In contrast, on-road transportation is represented by flow on edges which equals timber volume transported on an existing and newly constructed road.

The solution methods of most studies in Table 1.1 employ of a shortest path algorithm somewhere in the procedure. For example, in [24, 25], an iterative improvement algorithm named NETWORK [114] was employed, in which each iteration uses a shortest path algorithm. The shortest path heuristic (SPH) for solving the Steiner tree problem [130] consists of successively using a shortest path algorithm, was also often employed. To apply the SPH to a graph representing a potential road network without timber harvesting operations only is a main procedure in [41], and also used to obtain an initial solution which is the supplied to meta-heuristic algorithms in [84, 88]. In [79, 132], a solution method based on principles of cost-benefit analysis analyzing costs and benefits derived from road construction was proposed.

1.2.2.3 Graph representation of the potential road network

A distinct difficulty in modeling FRND is the graph representation of the potential road network, which has a substantial impact on road network layouts [121, 126]. Even if FRND is solved optimally as a combinatorial optimization problem, the generated road network will be neither truly optimal nor field–applicable as long as the potential road network is modeled by an insufficient graph representation which produces unrealistic road alignments. To ensure the success of road network design, an appropriate graph representation for a potential road network must be selected with care.

Table 1.2 Table summarizes graph representation of potential road networks in previous studies. Most previous studies related to FRND [e.g., 24, 25, 33, 79, 88, 108, 132] have employed the 8–neighbor representation. Here every node has eight neighbors, one node is located at each grid point of a square grid, and the road section of each edge is rendered as a straight line segment connecting the endpoints (Fig. 1.1a). Road networks generated on the basis of this simple representation are composed of straight line segments only, and contain no curved segments. As this is unrealistic and results in a violation of road design specifications, they are not directly applicable to field use. There is also an inherent risk of generating unfeasible zigzag road alignments (Fig. 1.1b), especially in steep terrain. To overcome this drawback, an elaborate graph representation was developed [for details, see 41, 126]. The main characteristics of this representation are the following: (*i*) every node has many (more than eight) neighbors, (*ii*) a node is attributed with a direction in a given set D of possible directions through which a road alignment passes, (*iii*) nodes whose number is equal to that of directions in D and whose directions differ from each other are located at each grid point of a square grid, and (*iv*) the road section of each edge is composed of one straight line segment and one curved segment, and its road alignment passes through the directions of the endpoints (Fig. 1.2). Use of this representation allows taking into account restrictions of minimum horizontal curve radius and the design of smooth and diverse road alignments. These characteristics are of pivotal importance for designing field-applicable road networks in steep terrain. However, the method has the disadvantage of generating very large graphs compared with the 8–neighbor representation.

1.2.3 Timber transportation

Decisions regarding the transportation of logs piled at roadsides emerge on a day-to-day basis and are also intimately associated with supply chain management in forestry. Timber transportation costs account for a significant fraction of the total costs of timber production. Improvement of the efficiency of timber transportation by rational transportation planning is therefore of significant interest . Many mathematical programming models have been developed to support transportation decisions, depending on the actual planning conditions [for details, see 32, 42, 106, 148]. Such models can provide practical transportation plans [e.g., 7, 17], and are supported by the development and improvement of GIS (geographical information systems) databases of forest resources and road routes.

The basic mathematical programming model for timber transportation planning is as follows [43].

$$\text{minimize} \qquad F = \sum_{i \in I} \sum_{j \in J} c_{ij} \cdot x_{ij} \tag{1.1}$$

$$\text{subject to} \quad \sum_{j \in J} x_{ij} \leq s_i \qquad \forall j \in J \tag{1.2}$$

$$\sum_{i \in I} x_{ij} = d_j \qquad \forall i \in I \tag{1.3}$$

$$x_{ij} \geq 0 \qquad \forall i \in I, j \in J \tag{1.4}$$

where I is a set of supply points, J is a set of demand points; c_{ij} and x_{ij} are the transport unit costs from supply point $i \in I$ to demand point $j \in J$ and the transportation amount (m^3), respectively; s_i is the volume of logs harvested in supply point i and d_j is the volume of logs that demand point j requires. The objective function 1.1 is the total transportation cost F. Equation 1.2 denotes that the amount of logs transported from supply point i is less than or equal to the supply volume of i. Equation 1.3 denotes that the amount of logs transported to demand point j is equivalent to the demand volume of j. Equation 1.4 is a non–negative constraint equation that shows that the transportation amount x_{ij} is not negative.

1.3 Objectives and outline of thesis

The main objective of this research was to mathematically describe four representative forest planning problems at the operational level: the multiple target access problem (Chapter 2); the forest road network design problem with timber harvesting operations (Chapter 3); the cable corridor layout problem (Chapter 4); and the timber transportation problem (Chapter 5 and 6). The former three problems, which include elements of network design, are formulated using a graph–theoretic approach. Additionally, heuristic algorithms for the formulated problems are described or proposed, and their performance is compared in terms of solution quality and computing time in computational experiments. The latter problem is formulated as a mathematical programming model. The reduction of transportation costs by selecting the type of transportation vehicle (Chapter 5) and using satellite yards (Chapter 6) are then quantitatively assessed using the model.

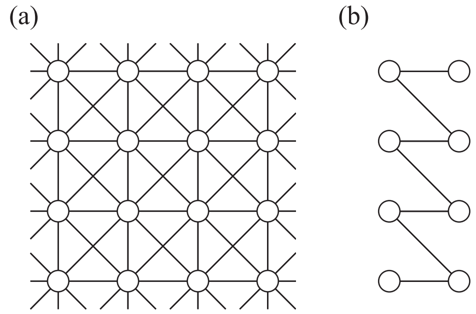

Figure 1.1: 8–neighbor graph representation of the potential road network - (a) graph and (b) zigzag road alignment

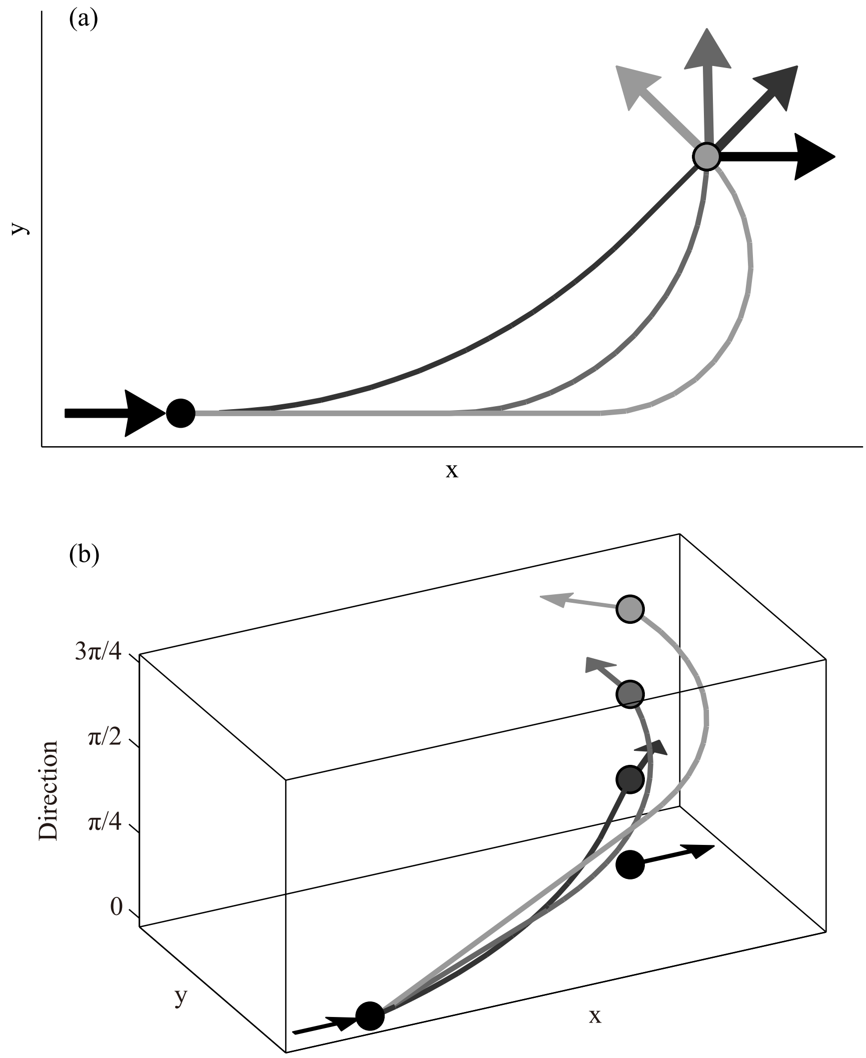

Figure 1.2: Elaborate graph representation of the potential road network - (a) two dimensional display and (b) three dimensional display

Table 1.1: Key characteristics for the literature on FRND with timber harvesting operations.

Article	Landing	Machinery	Skidding/yarding	On–road transp.	Underlying solution method
Bont et al. [15]			✗		MIP solver (ILOG CPLEX)
Chung et al. [24]	✗	✗	✗	✗	NETWORK [114]
Chung et al. [25]			✗	✗	NETWORK [114]
Epstein et al. [41]		✗	✗	✗	Shortest path heuristic [130]
Kobayashi [79]			✗		Cost-benefit analysis
Legües et al. [84]		✗	✗	✗	Tabu search
Meignan et al. [88]			✗		GRASP
Sakai [108]			✗		Minimum spanning tree heuristic [130]
Tan [132]			✗	✗	Cost-benefit analysis
Vera et al. [143]		✗	✗	✗	Lagrangian relaxation

Table 1.2: Key characteristics for graph representation of the potential road network in previous studies.

Reference	Arrangement of nodes	Node spacing (m)	Number of neighbors	Alignment model	Study site area (ha)
Sakai [108]	square grid	80	8	simple	256
Kobayashi [78]	square grid	250	8	simple	1444–2175
Liu and Sessions [86]	square grid	91.4	8	simple	480
Dean [33]	square grid	30	8	simple	
Tan [132]	square grid	50–400	8	simple	557
Heinimann et al. [66]	square grid	10	8, 24	simple, elaborate	100
Anderson and Nelson [4]	square grid with random shift	75^{ab}	20^{ac}	simple	7500
Chung et al. [24]	square grid	10	8	simple	93
Stückelberger et al. [124]	square grid	10	8, 24	simple, elaborate	3500
Epstein et al. [41]	square grid	10	16	elaborate	2–210
Picard et al. [99]	square grid	12	8	simple	133
Stückelberger et al. [126]	square grid	10	8, 24, 48	simple, elaborate	3500
Chung et al. [25]	square grid	69	8	simple	4760
Meignan et al. [88]	square grid	50	8	simple	2900-3153

Note: ^{a}Base case setting.
^{b}Maximum length of interval between neighbors.
^{c}Number of maximum neighbors per node.

2

A comparative study of heuristic algorithms for the multiple target access problem

2.1 Introduction

Extension of forest road networks is absolutely essential for forest resource utilization, because it improves accessibility to forest resources [60]. Decision-makers such as forest managers and engineers are tasked with designing efficient road networks to enhance accessibility while considering the environmental impact. The design process for road networks involves discrete decisions on the spatial arrangement of roads, for example, where to locate the straight line segments, curved segments, and branching points. An optimization model for designing forest road networks, which is induced by spatial elements and discrete structures inherent in the design process, occupies an important and permanent place in the field of spatial forest planning [26, 149]. Recently, the diffusion of high-resolution digital terrain models (DTMs) produced by airborne light detection and ranging (LiDAR) technology has increased the practical application of automatic design techniques for forest road networks [2, 6].

An optimization problem to determine forest road networks that best suit the decision-maker's goals belongs to a class of *network design problems* (ND). An ND, in general, requires a minimum (or maximum) subgraph of a weighted graph $G = (V, E)$ to be determined, where V is the node set and E is the edge set, subject to feasibility constraints [48]. This type of problem is commonly found in various real-life situations (such as designing telecommunications, power grids, and supply-chain networks). Because we are focused on a road network, the edge set and node set of G are regarded as a set of potential road segments and a set of endpoints for road segments, respectively, and the weights assigned to edges are equivalent road construction costs.

Many NDs belong to the NP-hard class with the exception of certain problems such as the shortest path problem or the minimum spanning tree problem (see Garey and Johnson [53], also for the definition of the class). Thus, these problems are intrinsically difficult to solve exactly from the standpoint of computational complexity theory. We cannot expect to apply an efficient (polynomial-time) exact algorithm for these problems and hence need to use heuristics, which can efficiently obtain near-optimal solutions even for large problems.

This paper addresses the *multiple target access problem* (MTA), which is a fundamental problem in forest road network planning. MTA was proposed by Dean [33], and an integer programming formulation for MTA was presented by Murray [91]. MTA aims to expand a road network from an existing road network with minimum construction cost, in order to allow access to given destinations (called targets) in forest areas. In forest science, several heuristics have been presented to solve this problem [4, 33, 99, 124]. However, comparative studies that evaluate the performance of heuristics for MTA in common grounds have been scarce: Dean [33] and Picard et al. [99] performed comparative experiments under simple and ideal situations, and Anderson and Nelson [4], Stückelberger et al. [124], and Stückelberger et al. [126] performed comparative experiments in which only a few problem instances were solved. Thus, which heuristic for MTA has superior performance remains to be answered.

In this study, we conducted computational experiments to compare the performance of many existing heuristics applicable to solve MTA. More specifically, we investigated the impact of heuristics on solution quality and computing time, through solving a large number of MTA instances under hypothetical but realistic situations. Before describing the experiments, we first show that, in ordinary cases, MTA is equivalent to the Steiner tree problem (ST) in graph theory. This allows us to use ST algorithms to solve MTA. Next, we present heuristics used in our experiments. Following the experiments, we identify the high-performance heuristics for MTA on the basis of the results, and also discuss the appearance characteristics of the road network layout designed by heuristics. The last section concludes this paper with suggestions for future research.

2.2 Materials and methods

2.2.1 Multiple target access problem

MTA on a graph can be stated formally as follows: Given a graph $G = (V, E)$ where each edge is assigned a road construction cost, a set of *targets* $T \subseteq V$ and a set of *existing nodes* $R \subseteq V$, find a minimum cost subgraph F of G such that there is a path from each target to one or more existing nodes. Targets are destinations (e.g., harvest sites or log landings) that must be reached by road extension. Existing nodes, which Murray [91] called “potential regional access locations,” are on an existing road network and are places from which new roads can be added. Figure 2.1 provides an example of MTA. In Fig. 2.1a, 25 nodes are serially established at grid points of a 5×5 square grid; the edges connect the four top and bottom, left and right nodes; and there exist five targets and three existing nodes. Note that the edges of the graph depicted in Fig. 2.1 (also in Figs. 2.2, 2.3, and 2.4) are considered conceptual connections by potential road segments between two nodes, and are not road alignments. Figure 2.1b shows an optimal subgraph of a graph in Fig. 2.1a.

Murray [91] indicated the similarities between MTA and ST. ST on a graph is an important problem in network design and can be described as follows [53]: Given a weighted graph $G = (V, E)$ and a subset of required nodes called *terminals* $Z \subseteq V$, find a minimum cost subtree H of G that includes all the terminals. Indeed, targets and terminals assume the same role as they must be included in the solution. Nevertheless, the number of connected components of solutions may differ between the two problems; that is, the number is always one in ST, and by contrast, is variable in MTA, as the subgraph shown in Fig. 2.1b is composed of three connected components. Murray [91] concluded that MTA is a separate and more difficult problem than ST because of this difference.

However, contrary to Murray’s (1998) conclusion, it is possible to describe that, in the majority of cases, MTA is equivalent to ST. Existing nodes function as an origin of road extension. Note that, with regard to function, it is not necessary to make a distinction among existing nodes, although their spatial positions are completely different from one another. Thus, we can identify existing nodes on a conceptual basis. In order to apply this to graph structure, let us introduce a standard graph-theoretic operation, *node identification*. Identifying nonadjacent nodes i and j as a single node k means that i and j are deleted, k is added, and all the edges that were incident to either i or j are reconnected to k [13]. Identifying existing nodes 2, 5, and 16 in Fig. 2.1a as a single existing node r results in a new graph, which is shown in Fig. 2.2*a*. Figure 2.2*b* shows an optimal subgraph for the problem in Fig. 2.2a. It is obvious that both MTA before and after identification of existing nodes are essentially the same, as the goal does not change as a result of node identification and both obtained subgraphs represent the same road network (Figs. 2.1b and 2.2b). A subgraph obtained by solving the MTA arisen after node identification has a tree structure and is composed of one connected component as shown in Fig. 2.2b. In addition, it is not necessary to distinguish between targets and a single existing node r generated by identifying the existing nodes, because targets and r play the same role as ST terminals that need to be connected. We can restate MTA after node identification in the form of ST as follows: Given a weighted graph $G = (V, E)$ and a set of terminals $Z = T \cup \{r\}$, $Z \subseteq V$, find a minimum cost subtree H of G that includes all the terminals. Consequently, we can say that MTA is, in general, equivalent to ST.

However, there are a few exceptions where MTA is not equivalent to ST, which result from an additional requirement such that some targets must be accessed from specific existing nodes. This requirement does not enable us to identify all existing nodes as a single node. The subgraphs in Figs. 2.2b and 2.3b are infeasible, if in the graph in Fig. 2.2a, subsets T_1, T_2 of the target set must be accessed from subsets R_1, R_2 of the existing node set, respectively, where $T_1 = \{6, 8, 13\}$, $T_2 = \{4, 8, 24\}$, $R_1 = \{2, 16\}$ and $R_2 = \{5\}$. In this case, the graph in Fig. 2.2a can be converted into that in Fig. 2.3a by identifying existing nodes in each subset R_1 and R_2 as r_1 and r_2. An optimal subgraph is illustrated in Fig. 2.3b. The MTA with this additional requirement is the (edge-sharing) multiple ST, which is a generalized ST [for details, see 70, 105]. The MTA discussed below does not have any additional requirement because this type of requirement is not general.

2.2.2 Heuristics for MTA

Here we present algorithms applicable to solving MTA and those used in our experiments. As explained in the preceding section, MTA can be transformed into ST by identifying existing nodes. Therefore, ST algorithms are applicable to solving MTA after transformation.

A considerable number of algorithms have been proposed that solve ST to optimality or near-optimality [70, 100, 146]. ST, i.e., MTA is NP-hard, and realistic MTA is not small enough to be solved exactly in reasonable time. Therefore, we need to use heuristics in an attempt to solve it. An effective class of heuristics is metaheuristics (such as genetic algorithm and tabu search), which were employed to solve forest road network design problems different from MTA [22, 84]. However, in general, metaheuristics require cautious tuning of many parameters and search components to provide superior performance, and even then, solution quality is not guaranteed [131]. Therefore, they were excluded in this study, and instead we used classical heuristics whose working procedures are rigorously defined.

The 14 heuristics employed in our experiments are listed in Table 2.1. Rayward-Smith and Clare [103], Voß [144], and Winter and Smith [154] conducted a comparative study of representative heuristics for ST in undirected graphs. These three studies conducted computational experiments where various STs in terms of input graph properties (e.g., numbers of nodes and terminals) were solved, to compare the performance of their heuristics. An outline of the heuristics employed in these studies is presented in Table 2.1. Most of them guarantee worst-case performance in terms of solution quality and time complexity. Importantly, for any ST, we always obtain a near-optimal solution with a cost that is at most twice the cost of the optimal solution, using the heuristics that have a worst-case performance ratio of $2(1 - 1/|Z|)$. Subsequently, each heuristic will be indicated by the abbreviation given in the table. With one exception, the names and abbreviations of the heuristics correspond with those in Hwang et al. [70] and Winter and Smith [154]. The exception, SPH-3 represents CHINS-3 in Voß [144].

The basic working principles or ideas of their heuristics are described briefly as follows, but for their detailed working procedures, please refer the three papers or Hwang et al. [70]. ADH begins with an initial solution that consists of terminals only, and then iteratively connects two subtrees in the tentative solution by using shortest paths from a node with the smallest f-value, until the solution becomes a tree. The f-value of node i indicates the level of proximity between node i and subtrees in the tentative solution. DAH is inspired by the dual of the multi-commodity flow formulation of ST. DNH constructs a minimum spanning tree of the complete graph with edges that are consistent with shortest paths between terminals. KBH is an adaptation of Kruskal's minimum spanning tree algorithm [82] to ST. LPH and SPH start with an arbitrarily chosen terminal and extend a tree by adding the shortest path to the farthest terminal and the closest terminal, respectively. SPH is also an adaptation of Prim's minimum spanning tree algorithm [101] to ST. MSTH constructs a minimum spanning tree of an input graph and then prunes the tree by removing redundant edges for spanning all terminals. SPH-3 is an altered SPH, where three components are united in each iteration. SPH-V, SPH-Z, SPH-zZ and SPH-ZZ are repetitive applications of SPH. SPH-V repeats SPH $|V|$ times, each time starting with a different node. SPH-Z repeats SPH $|Z|$ times, each time starting with a different terminal. SPH-zZ repeats SPH $|Z| - 1$ times, each time starting with a shortest path from an arbitrarily fixed terminal to every other terminals. SPH-ZZ repeats SPH $|Z|(|Z|-1)/2$ times, each time starting with a shortest path between each pair of terminals. After the repetition, they finally output the best tree. SPOH constructs a tree that consists of shortest paths from an arbitrarily chosen terminal to all other terminals. YH is similar to ADH, but YH iteratively connects three subtrees in concordance with the f-value. There is also a difference in computational methods used for the f-value between ADH and YH [144].

The above mentioned heuristics were developed in discrete mathematics, specifically graph theory; however, heuristics for the MTA developed or used in the field of forest science have high similarity to some of the heuristics listed in Table 2.1. For example, the heuristics called "independent paths with reduction" and "fully independent paths technique" in Dean [33] are MSTH and SPOH, respectively; Also, the basic ideas of the heuristics of Anderson and Nelson [4] are identical to those of LPH and SPH. Finally, the heuristics used in Stückelberger et al. [124] are DNH and a hybrid heuristic that combines DNH and simulated annealing.

2.2.3 Comparative experiments

All of the 14 heuristics were implemented using Matlab R2012b with the Parallel Computing Toolbox (PCT) [136], and the computational experiments were run on a 3.6

GHz Intel Core i7-3820 CPU with 16 GB RAM. In order to shorten the computing time, the following procedures were conducted on parallel computing, where PCT enabled us to run 12 workers (threads) concurrently on the multi-core processor: (a) the calculation of the f-value in ADH and YH, and (b) the repetition of SPH in SPH-V, SPH-Z, SPH-zZ and SPH-ZZ. When using LPH, SPH, SPH-3, SPH-zZ, and SPOH, a single arbitrary terminal had to be chosen as a starting node. In our experiments, node r generated by node identification of existing nodes was set as a starting node, because in MTA, r is the only terminal that is not originally a target.

In the following section, we describe how to represent potential road segments using a weighted graph and how to generate problem instances to be solved in our experiments. Additionally, we explain preprocessing operations on input graphs and postprocessing operations on output graphs, i.e., solutions obtained by heuristics for shortening the computing time and/or enhancing solution optimality.

2.2.3.1 Graph-theoretic representation of potential road network

A set of potential road segments was modeled using a square grid graph, where each node has eight neighbors and the edges are undirected (Fig. 2.4). All nodes are located on terrain, and the road alignment of each edge is rendered as a line segment connecting two nodes. This representation of road segments is used mostly in studies related to forest road network planning using graph-theoretic techniques [e.g., 24, 25, 33, 86, 88, 99, 132]. Focusing on the recent studies, where it has been relatively easy to use high-resolution DTM, there are two main types of node spacing—the side length of a square grid: 50 m or more [25, 88] and 10 m or more [24, 99]. Here, we adopted grid graphs of the two node spacings: a 50 m grid graph and a 10 m grid graph.

2.2.3.2 Edge weighting functions

MTA aims to minimize the total road construction cost incurred for the extension of road networks, and hence, the edges of an input graph are weighted by a weighting function for estimating construction costs. Construction costs of forest roads depend not only on road length but also on the topographical and geological properties of road routes, for example, terrain slope and subsoil composition [125].

We employed two types of weighting functions to calculate route-dependent weights corresponding to construction costs. Let $w(i, j)$ denote a weight function that assigns a weight to edge (i, j). The first was the slope factor function $w_{sf}(i, j)$ of Chung et al. [25], which represents the effect of terrain slope on construction costs. It is defined as follows:

$$w_{sf}(i, j) = d(i, j) \times mul_1(i, j) \times mul_2(i, j) \tag{2.1}$$

where $d(i, j)$ is the the distance, $mul_1(i, j)$ is the side slope multiplier, and $mul_2(i, j)$ is the road grade multiplier, between nodes i and j. The values of both multipliers, $mul_1(i, j)$ and $mul_2(i, j)$ follow those of Chung et al. [25]. The second function was the earthwork volume function $w_{ev}(i, j)$. Earthwork volumes have a considerable effect on construction costs, especially when very low-volume forest roads (e.g., spur roads) are constructed. This is because for such roads, simple pavement structures and few retaining structures are established, and therefore, earthwork costs account for a high percentage of the total construction cost. The function $w_{ev}(i, j)$ is defined as follows:

$$w_{ev}(i, j) = vol_{\text{cut}}(i, j) \times f_{\text{shr}} + vol_{\text{fill}}(i, j) \tag{2.2}$$

where $vol_{\text{cut}}(i, j)$ and $vol_{\text{fill}}(i, j)$ are the cut and fill volume (m^3), respectively, which result from the road construction between nodes i and j; and f_{shr} is a shrinking factor of earth volume fill: cut ($f_{\text{shr}} = 0.90$ in this study). Earthwork volumes were calculated using the average-end-area formula [156]. In our experiments, we assumed the road standard indicated in Table 2.2. Moreover, road cross sections were created at 2.0 m intervals in order to calculate slope factors and earthwork volumes.

2.2.3.3 Problem instances

The study area was a square of 4,000 ha in the Kamikawa District, Hokkaido, Japan (Fig. 2.5). This area is mostly covered by forests and has few roads. We divided the area into four square project sites of 1,000 ha each and numbered them as shown in Fig. 2.5b. Then, we installed the existing nodes at the four corners of their sites. Existing roads actually do not exist in their positions, and their existing nodes are imaginary. In this area, the Geospatial Information Authority of Japan has provided a 5 m DTM derived from airborne LiDAR data [54]. The DTM was used to calculate the two types of edge weights (slope factors and earthwork volumes). The average terrain slope of each site was calculated using the DTM, and the values in order of project site number 27.2 %, 29.0 %, 32.8 %, and 33.0 %. Suppose, for each project site, we are given a weighted graph that represents potential road segments, and a target set, and we would like to design the optimal road network, namely, the minimum weight subgraph in which all the targets are accessible from at least one of the four existing nodes.

The number of targets $|T|$ is varied according to not only circumstances of project sites, but also to what a target means (For instance, targets can be harvest sites or log landings). $|T|$ was small and set to about 3 per 1,000 ha by Stückelberger et al. [126], and about 25 per 1,000 ha by Anderson and Nelson [4]. In our experiments, $|T|$ had the following values:

- $|T| = 3, 6, 9, 12, 18, 24, 30.$

A target set was randomly generated, but to eliminate any effect of the difference in the target positions, the same target set was used even if the graphs were defined by a different node spacing or a different weighting function. The procedure to generate a target set is as follows: (i) a 50 m grid graph and a 10 m grid graph were installed in such a way that a subset of nodes is the same and spatially overlaps in both graphs (Fig. 2.6). Let W denote a set of nodes that are included in both graphs, as indicated by gray circles in Fig. 2.6. (ii) The required number of targets were chosen randomly from among the nodes in W. This procedure was repeated 10 times for each project site and for each number of targets. As a result, we prepared a family $\mathcal{T}_i$ composed of 70 target sets relevant to project site No i: $\mathcal{T}_i = \{T_{3,1}, T_{3,2}, \ldots, T_{3,10}, T_{6,1}, \ldots, T_{24,10}, T_{30,1}, \ldots, T_{30,9}, T_{30,10}\}$, where $T_{j,k}$ denotes a target set with j number of elements and an iteration number of k.

Ultimately, the problem instances were generated for each combination of:

- node spacing $= 50$ m, 10 m.
- weighting function $= w_{sf}, w_{ew}$.
- project site No $i = 1, 2, 3, 4$.
- target set in $\mathcal{T}_i = T_{3,1}, T_{3,2}, \ldots, T_{30,9}, T_{30,10}$.

Therefore, the number of problem instances that each heuristic solves was $2 \times 2 \times 4 \times 70 = 1,120$.

2.2.3.4 Preprocessing and postprocessing

In order to transform MTA into ST, the existing nodes of an input graph were changed to a single existing node r by node identification. Also, we removed the following edges from an input graph: (a) redundant edges not in the connected component containing r, and (b) infeasible edges whose road alignments violate either regulation for road standards. In this study, regulations were applied to the maximum road grade and the maximum side slope. We consider the graph subjected to the above preprocessing operations "the original graph G_0", because their operations are very basic and intuitively natural.

We reduced G_0 using graph-theoretic reduction techniques as a preprocessing operation. In general, reduction of a problem instance while maintaining the optimal solution is beneficial in terms of both computing time and memory requirement. For ST, reduction has been well established as a significant preprocessing operation [100] and may also enhance the performance of heuristics [36]. We employed the reduction routine of Esbensen [45] as shown in Fig. 2.7. This routine consists of four reductions described by Winter and Smith [154] and repeats them until the graph size no longer decreases. Reductions of types a and b are about nodes of degrees 1 and 2, respectively. In reductions of type c, an edge is removed if edge (i, j) is not the shortest path between nodes i and j. Reductions of type d contract an edge incident to a terminal if the edge must be included in the optimal solution.

On the other hand, as a postprocessing operation, we employed the improvement procedure introduced by Rayward-Smith and Clare [103], which was used successfully in Voß [144] and Winter and Smith [154]. This procedure is applied to each solution H obtained by heuristics and goes through the following steps: (i) Let V_H denote the node set of H and G_H denote a subgraph of G_0 induced by V_H, and determine the minimum spanning tree of G_H. (ii) Remove nodes which are not terminals and whose degree is 1 from this minimum spanning tree. In the next section, we will use the term "solutions" to refer to solutions after applying this improvement procedure.

2.3 Results and discussion

2.3.1 Size of problem instances and effect of reductions

The characteristics of our problem instances and reduction results are given in Table 2.3, purely in terms of graph size. The original graphs have, on average, 3,751.3 and 83,104.0 nodes in the respective 50 and 10 m grid graphs. Considering that, in the computational experiments of Rayward-Smith and Clare [103], Voß [144], and Winter and Smith [154], the problem instances had no more than 100 nodes, our problem instances are very large. Moreover, compared to the Steinlib testdata library [80], which has well known benchmarks for ST, the problem instances of the 10 m grid graph would belong to the largest class.

As understood from the comparison of the sizes before and after the reduction routine, the original graphs were effectively reduced by the routine. Specifically, there was a massive reduction in graphs with edges weighted by the earthwork volume function w_{ev}, and the reduction rate of the number of edges was greater than 40%.

A difference in reduction rate was observed between graphs with edges weighted by w_{sf} and those by w_{ev}. It is unlikely that the difference is caused mainly by reductions of types a and b focused on node degree, considering that the graph structure before reduction is the same regardless of the type of weighting function. Likewise, reductions of type d strongly related to terminals can have less effect on the difference, because the number of terminals is very small compared to that of nodes in this study. Therefore the major cause of the difference may be due to reductions of type c. These reductions are ineffective to graphs that satisfy the triangle inequality [154]. A typical example of such a graph is a Euclidean graph with edges weighted by the Euclidean distance between nodes. The fact that reductions of type c work better in w_{ev} than in w_{sf} indicates that earthwork volume as an edge weight is less distance-dependent (i.e., road-length-dependent) and more route-dependent than a slope factor.

2.3.2 Solution quality

We used two measures to compare solutions obtained by the 14 heuristics in terms of solution quality. The first measure was the frequency at which the best solution was found for each heuristic. The second measure was the percentage of deviation from the best solution for each solution, which is given as follows:

$$dev = \frac{val - val_{best}}{val_{best}} \times 100 \tag{2.3}$$

where *dev* is the percentage of deviation, *val* is the value of the solution for comparison and val_{best} is the value of the best solution. The "best solution" that we refer to here indicates the solution of the minimum value among the 14 solutions obtained by the heuristics, and is not an optimal solution of the problem instance, because we do not obtain an optimal solution in a realistic time frame.

Figure 2.8 shows changes in the best solution frequency as a function of the target number $|T|$. The figure is shown for each combination of node spacings and weighting functions. (The same applies to Figs.2.9–2.12 and 2.14.) The frequency was calculated by (i) counting the number of times each heuristic obtains the best solution in 40 problem instances with the same node spacing, the same weighting function and the same target number, but with different project site, and (ii) multiplying the number by 100/40. Note that the sum of frequency for each target number exceeds 100 % because the same best solution is obtained by different heuristics. For SPH, SPH-Z, and SPH-V, if SPH obtains the best solution, SPH-Z and SPH-V always obtain the same because SPH is involved in SPH-Z and SPH-V. If SPH-Z obtains the best solution, SPH-V always obtains the same because SPH-Z is involved in SPH-V. Similarly, the same relationship exists between SPH-zZ and SPH-ZZ.

A few targets made the MTA simple, and different heuristics could reach the same solution. Thus, when $|T| = 3$, there was a tendency for more than one heuristic to obtain the same best solution, and hence, many heuristics represented a certain level of frequency. This tendency quickly disappeared with increasing $|T|$. Then, ADH and the repetitive SPH variants (SPH-V, SPH-Z, SPH-zZ and SPH-ZZ) almost always outperformed all of the other heuristics regardless of the types of node spacings and weighting functions. Specifically, SPH-V and SPH-ZZ generally behaved best and exhibited a relatively high frequency, which agrees with the results of Winter and Smith [154] despite radical differences in the size of problem instances. However, in our results, only ADH exceptionally surpassed both heuristics.

The changes in the average *dev* and maximum *dev* as a function of $|T|$ are shown in Figs. 2.9 and 2.10. For each heuristic, the average *dev* was calculated by averaging the *dev* of 40 problem instances whose node spacings, weighting functions and target numbers were the same, but project site was different. By contrast, the maximum *dev* was the maximum value of *dev* of the 40 problem instances.

In general, the order of superiority of the heuristics was relatively stable and seems less related to node spacings, weighting functions and target numbers, with respect to both average *dev* and maximum *dev*. The values in graphs weighted by w_{sf} tend to be larger than those in graphs weighted by w_{ev}, with particular reference to the average *dev*.

In ADH, SPH and its variants (SPH-3, SPH-V, SPH-Z, SPH-zZ, and SPH-ZZ), the values of the average *dev* were very low at less than a small percentage (Fig. 2.9), and those of the maximum *dev* were within 20 % in all the problem instances (Fig. 2.10). In particular, as predicted from the results with the the best solution frequency, ADH and the repetitive SPH variants were the dominant heuristics. However, note that some heuristics have a performance not significantly inferior to those mentioned above. With respect to the average *dev*, DAH, KBH, LPH, and YH had values within about 10 %–30 % in w_{sf} and within 10 % in w_{ev}.

2.3.3 Computing time

We measured the computing time required to solve a problem instance. Figure 2.11 illustrates the change in computing times as a function of $|T|$. The computing time shown in the figure is the average of computing times for 40 problem instances with the same node spacings, weighting functions, and target numbers, but different project sites. The computing times increased with increasing $|T|$ in all heuristics except MSTH and SPOH. The main procedures of MSTH and SPOH solve once the minimum spanning tree problem and the shortest path problem without relation to targets, respectively, and hence their computing times are unaffected by $|T|$.

All problem instances of the 50 m grid graph were solved in less than 100 s in each heuristic (Figs. 2.11a and 2.11b). Meanwhile, in problem instances of the 10 m grid graph, the computing times of ADH, DAH, SPH-V, and YH were well over 1,000 s in almost all problem instances, and more than 5,000 s when $|T| = 30$ (Figs. 2.11c and 2.11d). It had been expected that ADH, SPH-V and YH would require very long computing times, because of their worst-case time complexity (Table 2.1) and the large size of the 10 m grid graph (Table 2.2). It actually turned out that in their three heuristics, the procedures on all the nodes (the calculation of the f-value in ADH and

YH; the repetition of SPH in SPH-V) greatly increased computing times, although we performed parallel computing in their procedures. It was shown that ADH, DAH, SPH-V, and YH have inferior performance in terms of computing time. If a responsive design process of road network is required, attention must be paid to applying these heuristics to solve a large-scale MTA.

2.3.4 Road network layouts

Until now, it was shown that the three heuristics (ADH, SPH-V, and SPH-ZZ) achieve the same superior level of performance in terms of solution quality. Here we examine whether road networks designed by these heuristics are also similar in appearance. In Fig. 2.12, we illustrate examples of road network layouts designed by the three heuristics. As can be seen from the figure, most of road networks designed by the three heuristics resembled closely in appearance, when weighting functions and node spacings were the same. However, somewhat different layouts were observed. Prominent examples include layouts of sites 1, 2, and 3 in Fig. 2.12a, where layouts designed by ADH were different from those designed by SPH-V and SPH-ZZ.

In order to quantify the degree of shape similarity between road network layouts, we define the following similarity measure sim (%). Assume that we calculate sim between road networks $road_\alpha$ and $road_\beta$ designed by heuristics α and β, respectively. (i) Overlay a square mesh on the layouts. (ii) Identify mesh cells including roads. Let C_α and C_β denote a set of mesh cells including roads of $road_\alpha$ and $road_\beta$, respectively. (iii) Calculate sim (%) using the following equation.

$$sim = \left(\frac{|C_\alpha \cap C_\beta|}{|C_\alpha|} + \frac{|C_\alpha \cap C_\beta|}{|C_\beta|} \right) \times \frac{1}{2} \times 100 \tag{2.4}$$

The first and second terms are interpreted as a measure of how much $road_\alpha$ and $road_\beta$ correspond (roughly) to $road_\beta$ and $road_\alpha$, respectively, from a locational standpoint. In the example illustrated in Fig. 2.13, $|C_\alpha| = 10$, $|C_\beta| = 11$ and $|C_\alpha \cap C_\beta| = 7$, and hence $sim = 66.8\%$. The measure sim depends largely on the mesh size of an overlaying mesh. Then, we set the mesh size to 50 m and 100 m and calculated sim between two layouts for each pair of heuristics (ADH and SPH-V, ADH and SPH-ZZ, and SPH-V and SPH-ZZ) in all the problem instances. Figure 2.14 illustrates the change in sim as a function of $|T|$. Overall, the sim between SPH-V and SPH-ZZ was higher than that between the other pairs. This is because SPH-V and SPH-ZZ are variants of SPH, and their procedures are very similar to that of ADH. Yet the *sim* of the pairs (ADH and SPH-V, and ADH and SPH-ZZ) was greater than about 75 % in w_{sf} and about 90 % in w_{ev}. Hence, the layout produced by ADH was deemed to also bear substantial resemblance to those produced by SPH-V and SPH-ZZ. With some exceptions, the three heuristics basically output similarly shaped layouts with providing the same level of solution quality.

Besides the main objective of this study, we should refer to the impact of weighting functions and node spacings on the road network layouts. If the weighting function is different, the entity to be minimized changes; therefore, it is not surprising that different road network layouts were proposed between w_{sf} and w_{ew} (compare Fig. 2.12a with Fig. 2.12b or Fig. 2.12c with Fig. 2.12d). Of particular interest is a phenomenon whereby entirely different layouts sometimes resulted from differing node spacings, even when using the same heuristic (compare Fig. 2.12a with Fig. 2.12c or Fig. 2.12b with Fig. 2.12d). For example, a significant locational difference was observed between layouts of site 3 in Figs. 2.12a and 2.12c. This demonstrates that node spacings, i.e., graph-theoretic representations of potential road segments, had a profound impact on road network layouts. A similar phenomenon was also reported by Stückelberger et al. [126], who found that neighborhood patterns and road alignment models, which are directly associated with representations of potential road segments as with node spacings, cause differences in road network layouts. Because of the great impact on road network layouts, choosing the representation of road segments as well as weighting function is critical in planning the road network. An inappropriate choice leads to a graph that does not suitably reproduce potential road segments of a real situation, and, at worst, may bring about a graph in which a realistic set of good road networks never exist. Such a graph leaves no room for an optimal (near-optimal) road network in the true sense, regardless of which high-performance algorithm is used.

2.4 Conclusions and future work

We first showed that MTA is equivalent to ST on a graph when existing nodes can be identified, and then investigated the performance of 14 heuristics for ST in solving MTA. The reduction routine by Esbensen [45], as a preprocessing operation, powerfully reduced the size of problem instances. From the comparison of solution value, it was concluded that, in terms of solution quality, ADH and the repetitive SPH variants (SPH-V, SPH-Z, SPH-zZ and SPH-ZZ) have superior performance, which is less susceptible to the characteristics of MTA instances (i.e., node spacings, weighting functions and target numbers). In addition, by estimating the degree of shape similarity between road network layouts designed by ADH, SPH-V, and SPH-ZZ, we confirmed that their layouts show high shape similarity to one another. In terms of computing time, ADH, DAH, SPH-V, and YH required extended time to solve problem instances of 10 m grid graphs, and therefore, we should be cautious to solving a large-scale MTA using these heuristics.

In solving forest road network design problems exemplified by MTA, further algorithmic research suggesting high-performance heuristics is definitely warranted. Moreover, given the fact that the same heuristic designed entirely different road network layouts with different node spacings, future research should investigate appropriate graph-theoretic representations of potential road segments in designing truly optimal and field-applicable road networks. The adoption of elaborate representations such as that developed by Stückelberger et al. [126] can enhance road network alternatives; however, it increases the problem size and problem difficulty. Attention should be focused on the trade-off between enhancing the alternatives and increasing the problem size.

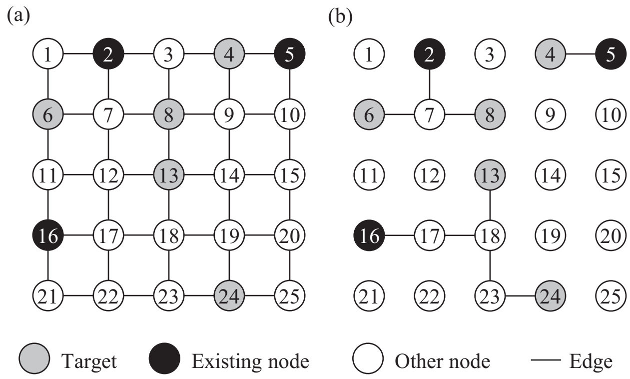

Figure 2.1: Graphical illustration of MTA - (a) an input graph, and (b) an optimal subgraph.

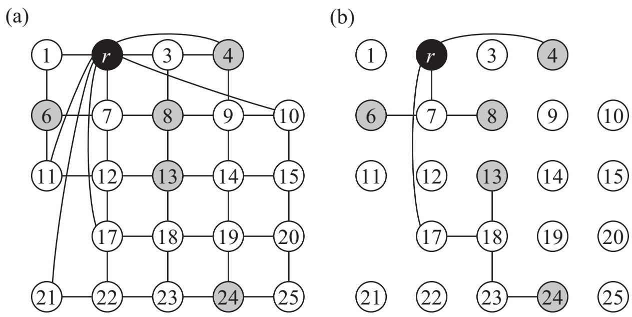

Figure 2.2: MTA after node identification of existing nodes - (a) an input graph, and (b) an optimal subgraph.

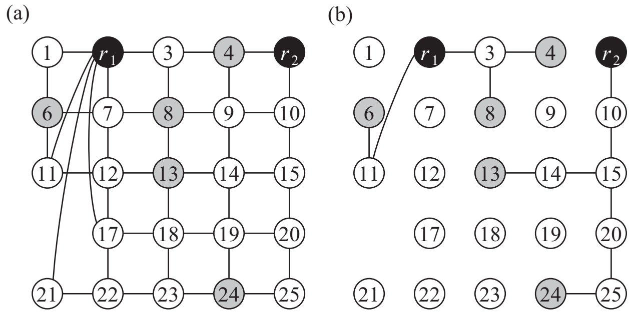

Figure 2.3: Exceptional MTA - (a) an input graph, and (b) an optimal subgraph.

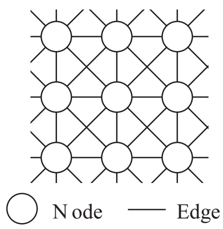

Figure 2.4: Eight-neighbor square grid graph -

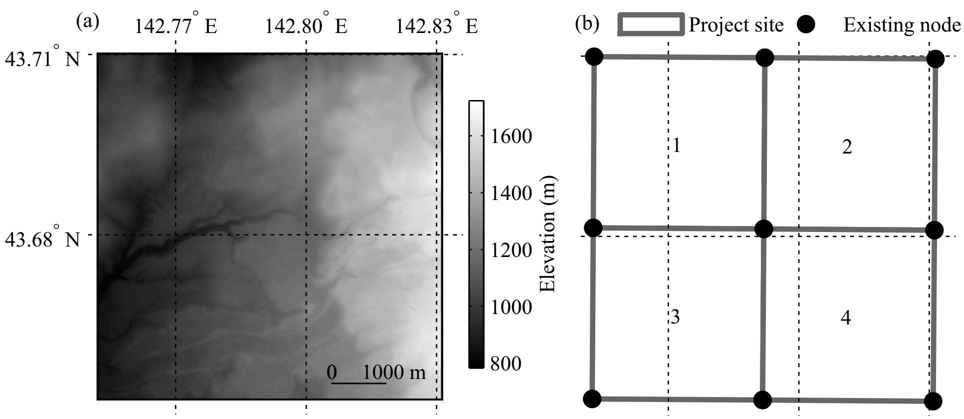

Figure 2.5: Study area in the Kamikawa District, Hokkaido, Japan - (a) elevation map, (b) terrain slope map, and (c) the four project sites and existing nodes.

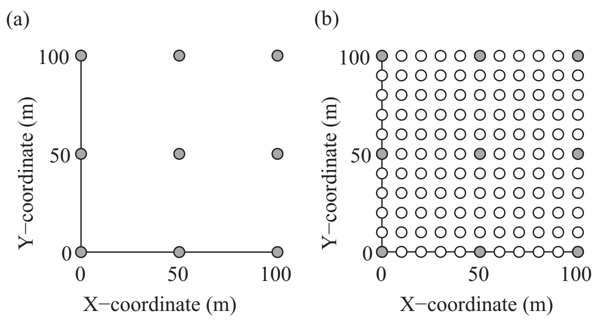

Figure 2.6: Arrangement of nodes - (a) the 50 m grid graph and (b) 10 m grid graph.

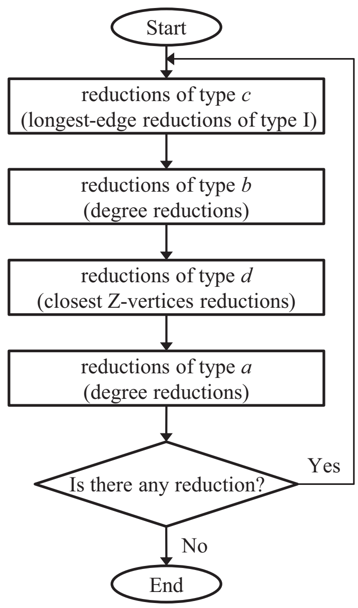

Figure 2.7: Flowchart of the reduction routine of Esbensen [45] - The names in parentheses are those used by Winter and Smith [154].

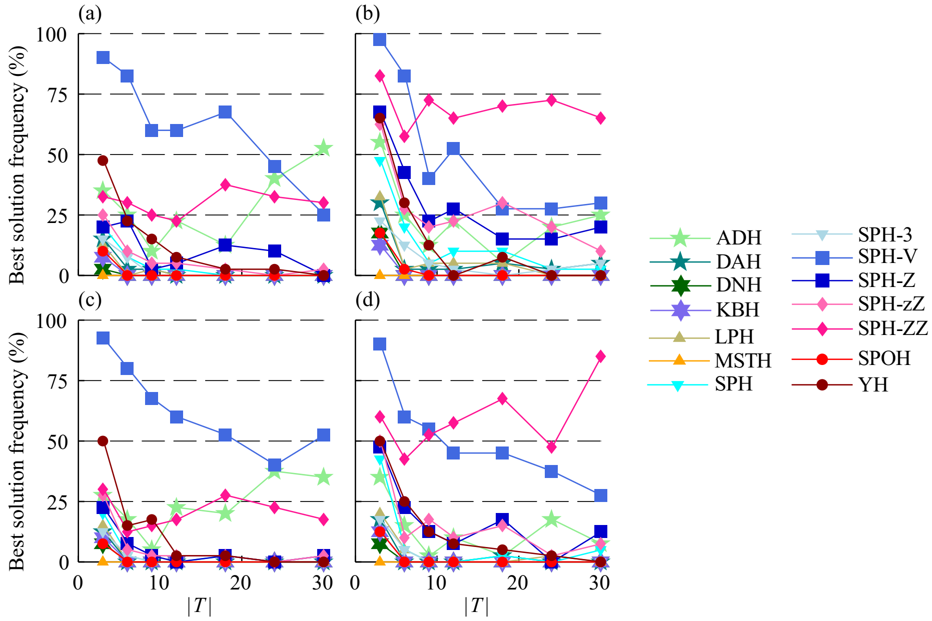

Figure 2.8: Best solution frequency - (a) 50 m grid and w_{sf}, (b) 50 m grid and w_{ev}, (c) 10 m grid and w_{sf}, and (d) 10 m grid m and w_{ev}.

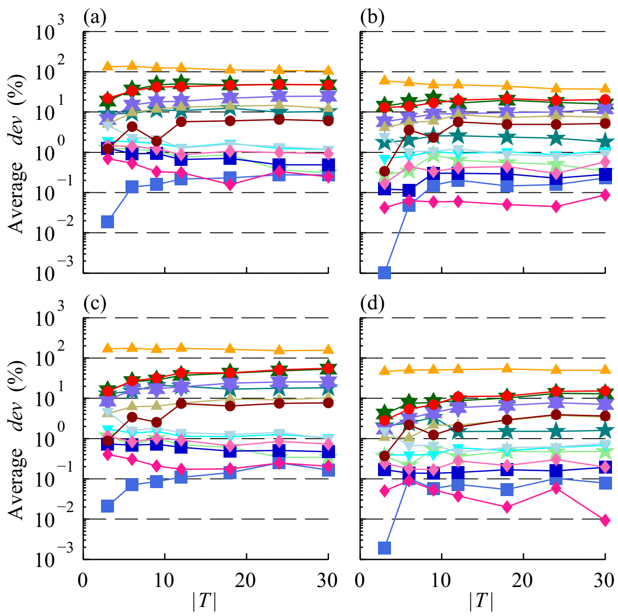

Figure 2.9: Average deviation from the best solution - (a) 50 m grid and w_{sf}, (b) 50 m grid and w_{ev}, (c) 10 m grid and w_{sf}, and (d) 10 m grid m and w_{ev}. Legend is the same as Fig. 8.

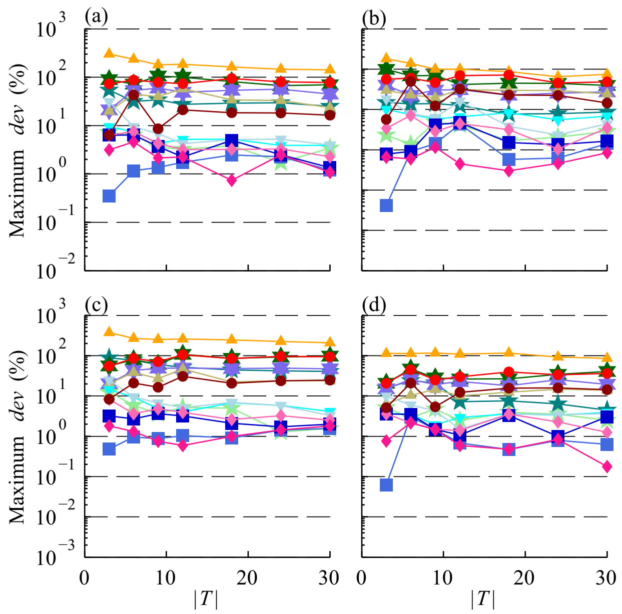

Figure 2.10: Maximum deviation from the best solution - (a) 50 m grid and w_{sf}, (b) 50 m grid and w_{ev}, (c) 10 m grid and w_{sf}, and (d) 10 m grid m and w_{ev}. Legend is the same as Fig. 8.

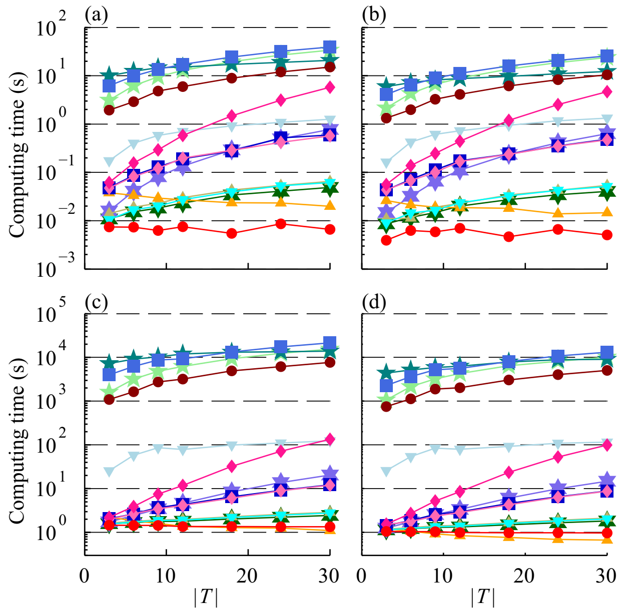

Figure 2.11: Computing time - (a) 50 m grid and w_{sf}, (b) 50 m grid and w_{ev}, (c) 10 m grid and w_{sf}, and (d) 10 m grid m and w_{ev}. Legend is the same as Fig. 8.

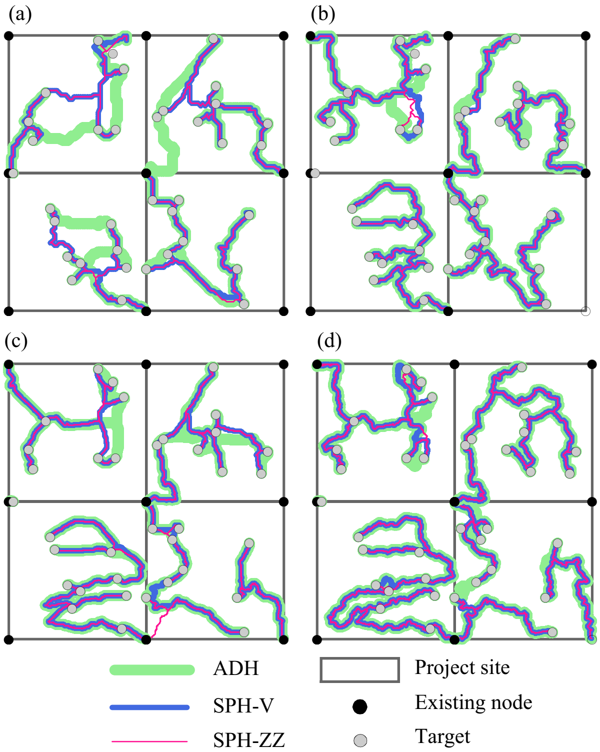

Figure 2.12: Road network layouts designed by three heuristics (ADH, SPH-V and SPH-ZZ) - (a) 50 m grid and w_{sf}, (b) 50 m grid and w_{ev}, (c) 10 m grid and w_{sf}, and (d) 10 m grid m and w_{ev}.

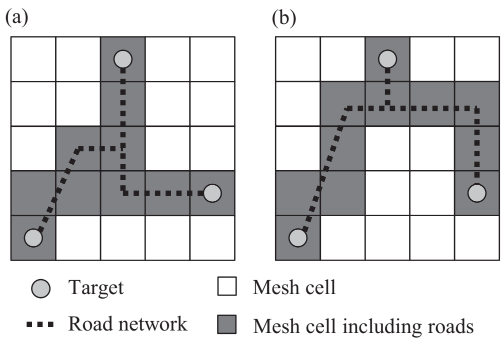

Figure 2.13: Overlaying a square mesh on road network layouts - (a) A road network $road_{\alpha}$ designed by heuristic α, and (b) a road network $road_{\beta}$ designed by heuristic β.

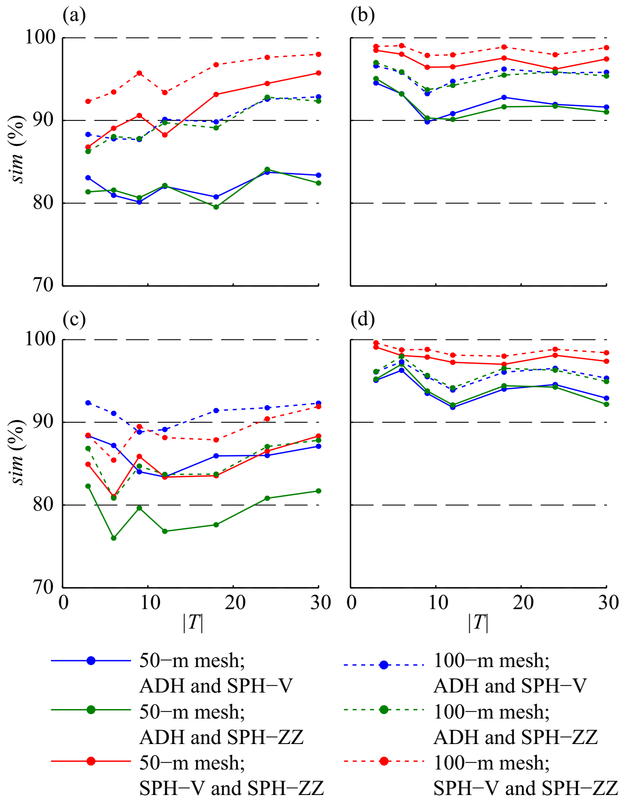

Figure 2.14: Degree of shape similarity between road network layouts - Comparison of road network layouts designed by three heuristics (ADH, SPH-V, and SPH-ZZ). (a) 50 m grid and w_{sf}, (b) 50 m grid and w_{ev}, (c) 10 m grid and w_{sf}, and (d) 10 m grid m and w_{ev}.

Table 2.1: Heuristics for ST in undirected graphs, compared in Rayward-Smith and Clare [103], Voß [144] or Winter and Smith [154].

Heuristic name	Abbreviation	Worst-case performance ratio	Worst-case time complexity	Reference
Average distance heuristic	ADH*†‡	$2(1-1/\lvert Z\rvert)$	$O(\lvert V\rvert^3)$	Rayward-Smith [102]
Dual ascent heuristic	DAH†			Wong [155]
Distance network heuristic	DNH*†‡	$2(1-1/\lvert Z\rvert)$	$O(\lvert E\rvert+\lvert V\rvert\log\lvert V\rvert)$	Kou et al. [81]
Kruskal-based heuristic	KBH‡	$2(1-1/\lvert Z\rvert)$	$O(\lvert Z\rvert\lvert V\rvert^2)$	Wang [147]
Longest path heuristic	LPH‡		$O(\lvert Z\rvert(\lvert E\rvert+\lvert V\rvert\log\lvert V\rvert))$	Winter and Smith [154]
Minimum spanning tree heuristic	MSTH‡	$\lvert V\rvert-\lvert Z\rvert+1$	$O(\lvert E\rvert+\lvert V\rvert\log\lvert V\rvert)$	Takahashi and Matsuyama [130]
Shortest path heuristic	SPH*†‡	$2(1-1/\lvert Z\rvert)$	$O(\lvert Z\rvert(\lvert E\rvert+\lvert V\rvert\log\lvert V\rvert))$	Takahashi and Matsuyama [130]
Shortest path heuristic with 3BA-SIC	SPH-3†			Voß [144]
Repetitive shortest path heuristics	SPH-V‡	$2(1-1/\lvert Z\rvert)$	$O(\lvert Z\rvert\lvert V\rvert^3)$	Winter and Smith [154]
	SPH-Z†‡	$2(1-1/\lvert Z\rvert)$	$O(\lvert Z\rvert^2\lvert V\rvert^2)$	Winter and Smith [154]
	SPH-zZ‡	$2(1-1/\lvert Z\rvert)$	$O(\lvert Z\rvert^2\lvert V\rvert^2)$	Winter and Smith [154]
	SPH-ZZ‡	$2(1-1/\lvert Z\rvert)$	$O(\lvert Z\rvert^3\lvert V\rvert^2)$	Winter and Smith [154]
Shortest paths with origin heuristic	SPOH†	$\lvert Z\rvert-1$	$O(\lvert E\rvert+\lvert V\rvert\log\lvert V\rvert)$	Takahashi and Matsuyama [130]
Y-heuristic	YH†	$2(1-1/\lvert Z\rvert)$	$O(\lvert Z\rvert^2\lvert E\rvert\log\lvert V\rvert)$	Chen [20]

* Compared in Rayward-Smith and Clare [103]. † Compared in Voß [144]. ‡ Compared in Winter and Smith [154].

Table 2.2: Road standard parameters assumed in our experiments.

Parameter	Value
Cut-slope angle	1 : 1
Fill-slope angle	1 : 1
Road width (m)	3.0
Maximum road grade (%)	20.0
Maximum side slope (%)	90.0

Table 2.3: Original and reduced graphs. The reduced graphs G_{sf} and G_{ev} result from reduction of the original graphs G_0 with edges weighted by the slope factor function w_{sf} and the earthwork volume function w_{ev}, respectively. $|V|$ and $|E|$ of the reduced graphs are averages taken over 70 problem instances with the same node spacing, weighting function, and project site, but with different target numbers. r_V and r_E represent the reduction rate of the number of nodes and edges, respectively, with respect to those of the original graph.

		G_0		G_{sf}				G_{ev}			
	Site No.	$\|V\|$	$\|E\|$	$\|V\|$	$\|E\|$	r_V	r_E	$\|V\|$	$\|E\|$	r_V	r_E
50-m grid	1	3,921	11,092	3,496.7	10,422.7	10.8	6.0	2,988.0	6,357.0	23.8	42.7
	2	3,812	10,503	3,105.1	9,545.3	18.5	9.1	2,510.8	5,310.3	34.1	49.4
	3	3,723	10,779	3,191.7	9,684.8	14.3	10.2	2,595.0	5,852.7	30.3	45.7
	4	3,549	10,032	2,945.9	8,883.2	17.0	11.5	2,328.2	5,128.5	34.4	48.9
	Average	3,751.3	10,601.5	3,184.8	9,634.0	15.2	9.2	2,605.5	5,662.1	30.7	46.7
10-m grid	1	94,000	266,497	81,241.7	252,040.8	13.6	5.4	72,417.5	148,857.7	23.0	44.1
	2	85,560	243,275	70,899.3	227,385.5	17.1	6.5	61,841.6	126,696.9	27.7	47.9
	3	81,769	230,513	67,874.6	213,012.1	17.0	7.6	56,487.5	120,694.2	30.9	47.6
	4	71,087	203,792	59,467.8	188,935.5	16.3	7.3	48,117.3	102,587.9	32.3	49.7
	Average	83,104.0	236,019.3	69,870.9	220,343.5	16.0	6.7	59,716.0	124,709.2	28.5	47.3

3

New heuristic algorithms for designing forest road networks suitable for timber harvesting operations

3.1 Introduction

Designing road network which provide access to timber resources and facilitate forest management activities remains a key challenge in forest planning. The field of forest planning in recent decades has developed models and techniques to support decision–making in forest management activities, while placing special emphasis on spatial elements and combinatorial nature of the planning process [8]. In such situation, road network has been recognized as an integral spatial element, and "how to locate road network in forest areas" i.e., forest road network design is one of fundamental subjects to be addressed in research [26, 149].

This paper addresses the task of designing forest road networks suitable for timber harvesting operations, which is practical and common for forest engineers. The task asks forest engineers to design a road network which minimizes the total cost incurred at road construction and timber harvesting operations. Naturally, the designed road network must satisfy the required road design specifications (e.g., the maximum road gradient and minimum horizontal curve radius). Simultaneously, they must achieve the required operational specifications for harvesting operations. For example, it is necessary to keep a distance from roadside to the timber resources below the maximum skidding/yarding distance which is determined by harvesting machinery used in the operations. Moreover, if cable yarding operations are done, attention needs to be paid to the feasibility of cable yarding, which depends on whether the cable is stretched between a head spar around roads and a tail spar without being influenced by terrain. Because forest engineers take into account cost minimization, road design specifications, operational specifications and geographic conditions as described above, the task is extremely complex, especially in mountainous forest areas in which steep geography imposes various restrictions on design options. The decision-making process related to the task forms one of the basis of operational forest management [119]. Some software packages such as PLANS [142], PLANZ [31] and PLANEX [41] were developed to support the decision–making process.

The main objective of this study is (i) to formulate the above task as a combinatorial optimization problem using a graph–theoretical approach, and (ii) to propose several new heuristic algorithms for the formulated problem. Furthermore, to compare the performance of our proposed algorithms with that of some existing algorithms, this paper performs computational experiments, where forest road networks are designed under realistic assumptions about road design specifications, operational specifications and geographic conditions.

This paper is organized as follows: In Section 3.2 some graph-theoretic preliminaries needed for the rest of the paper are given, and in Section 3.3 the framework of our problem formulation is presented. Section 3.4 describes both the existing and our proposed algorithms for solving the formulated problem. Section 3.5 and 3.6 contain our computational experiments and their results. Finally Section 3.7 provides concluding remarks.

3.2 Preliminaries

This section presents graph-theoretic definitions and notations to describe the problem we address and our proposed algorithms. A weighted directed graph G consists of a set of nodes $V(G)$, a set of directed edges $E(G)$ and a cost function $\omega : E(G) \to \mathbb{R}_+$ which assigns a cost with each edge. We denote the number of nodes in $V(G)$ by n, and the number of edges in $E(G)$ by m. Let e_{vw} and c_{vw} be a directed edge from node v to node w and the weight of the edge, respectively. We use P_{vw} to represent the shortest path from node v to node w in G. Additionally, the sum of the costs of the edges in P_{vw}, that is, the the shortest distance from node v to node w is denoted by d_{vw}.

The *directed Steiner tree* is defined as a rooted out-going tree consisting of directed paths from the *root* to all destination nodes called *terminals*. The tree can be referred as the *full Steiner tree*, especially when all the leaves are terminals and all the other nodes except leaves are not terminals [158]. The *directed Steiner tree problem* (DST) is formulated as follows: Given a weighted directed graph G, a root $r \in V(G)$, and a set of terminals $S \subseteq V(G)$, determine a directed Steiner tree $T = (V(T), E(T))$ with minimum cost. We denote the number of terminals in S by k. The undirected version of DST is called the (undirected) *Steiner tree problem* (ST). DST as well as ST are the fundamental problems in combinatorial optimization and an important practice for network design and routing [e.g., 35, 70]. Since ST is known to be NP-hard [53], we can not expect to find exact algorithms which solve the problem in polynomial time, unless P = NP. ST can be transformed into DST by converting each undirected edge to a pair of directed edges with opposite directions, and hence DST is also NP-hard. If $k = 1$ and $k = n$, DST reduces to the shortest path problem and the spanning tree problem in directed graphs, respectively. The both problems are polynomially solvable in $O(n^2)$ time using the shortest path algorithm such as Dijkstra's algorithm [34], or using a minimum spanning tree algorithm such as Edmonds's algorithm [38].

3.3 Problem description

The level of detail required in planning depends on what work processes are incorporated into the problem. The more work processes are incorporated into the problem, the more detailed and operational decisions (e.g., locating harvesting machinery and landings) can be made. On the other hand, it increases the problem size, and then can make the problem hard to solve. As can be seen from Table 1.1, the work processes incorporated into the problem differ among previous studies, but an indispensable process for modeling timber harvesting operations is skidding/yarding operations.

In this paper, we address the simplest problem involving road construction and skidding/yarding operations. The simplification of work processes except road construction and skidding/yarding operations is not only for the sake of reducing problem size. We omit landing construction and harvesting machinery installation from the problem, on the basis of the level of detail required in planning. It is assumed that when designing road networks for a certain size (some tens of hectares) of a planning area, forest engineers do not simultaneously determine concrete locations of harvesting machinery or landings. They probably first seek to determine road networks which ensure the sufficient potential of harvesting timber resources within the planning area while maintaining a rough balance between road construction costs and skidding/yarding costs. (Too much road construction leads an increase in road construction costs, whereas too little lengthens skidding/yarding distances and then leads an increase in skidding/yarding costs.) Since then, they determine concrete locations of harvesting machinery or landings. To determine the concrete locations, other specialized formulations such as [37] may be effective.

In addition, we simplify on-road transportation owing to the following reasons: (*i*) As mentioned in [41], on-road transportation costs are substantially smaller than road construction costs, and thus the simplification of on-road transportation produces little change in the problem itself. (*ii*) As for on-road transportation, it is necessary to introduce a continuous variable (flow on edges), unlike in other work processes represented by a discrete variable (edge). Thus, the incorporation of on-road transportation into the problem add computational aspects of mixed integer programming, and possibly increase the complexity of the problem.

3.3.1 Graph structure

Here we describes the structure of a directed graph $G = (V(G), E(G))$ in the problem. As a precondition, the graph has a root $r \in V(G)$.

A potential road network consists of a set of road nodes V_{road} and a set of road edges $E_{\text{road}} = \{(v, w) | v, w \in V_{\text{road}}\}$. Road nodes and road edges are regarded as endpoints for road sections and road sections, respectively. The road edges are weighted road construction costs by cost function $\omega_{\text{road}} : E_{\text{road}} \to \mathbb{R}_{+}$. Road sections corresponding to road edges must meet road design specifications. A set of existing nodes V_{exist}, which is a subset of V_{road}, is places on an existing road network and from which new roads can be constructed. To express the potentiality for new road construction from existing nodes, we introduce a set of imaginary edges $E_{\mathrm{img}} = \{(r, v)|v \in V_{\mathrm{exist}}\}$ that connect the root and existing nodes. The cost of imaginary edges is 0.

Let Z be a set of timber nodes, which are timber resources to be harvested. Skidding/yarding operations are represented by a set of skidding/yarding edges $E_{\mathrm{sy}} = \{(v, z)|v \in V_{\mathrm{road}}, z \in Z\}$. The skidding/yarding edges are weighted skidding/yarding costs by cost function $\omega_{\mathrm{sy}} : E_{\mathrm{sy}} \to \mathbb{R}_{+}$. A skidding/yarding edge whose one endpoint is road node $v \in V_{\mathrm{road}}$ and the other one is timber node $z \in Z$ indicates skidding/yarding operations where machinery hauls z from its initial position to roadside around v. Skidding/yarding operations corresponding to skidding/yarding edges must be feasible and comply with operational specifications. That is, terrain must not be a major obstacle in the operations, and also a distance between v and z must be shorter than the maximum skidding/yarding distance, which is determined by machinery used.

When the costs incurred in accessing a timber resource by road construction and harvesting it is considerably high, a forest engineer has the option of not harvesting its uneconomical timber resource. In order to make a decision regarding this no-harvesting, in [41], where timber resources are greedily added to the solution, the search is stopped when the average cost per timber volume incurred in the whole plan exceeds the criteria predefined by the engineer. We directly implement the no-harvesting decision by using a set of no-harvesting edges $E_{\mathrm{nohar}} = \{(r, z)|z \in Z\}$ that connect the root and timber nodes. The cost of no-harvesting edges is no-harvesting criteria α.

From the above description, the node set $V(G)$ and the edge set $E(G)$ equal $\{r\} \cup V_{\mathrm{road}} \cup Z$ and $E_{\mathrm{road}} \cup E_{\mathrm{sy}} \cup E_{\mathrm{img}} \cup E_{\mathrm{nohar}}$, respectively. Figure 3.1a depicts schematically, the graph. There are two types of directed paths from the root to a timber node. The first, which represents road construction and skidding/yarding operations to harvest timber resources, consists of one imaginary edge, a number of road edges and one skidding/yarding edge, in sequence. In contrast, the second, which represents not harvesting timber resources, consists of only one no-harvesting edge. Figure 3.1b illustrates an example of a solution, where one timber node is harvested and the other not. A solution from an undirected graph (Fig. 3.1c) shows that the graph must be directed, because the solution is infeasible in the real world.

3.3.2 Problem formulation

The problem can be formally formulated in the form of DST, by regarding a set of timber nodes Z as a set of terminals S: Given a weighted directed graph G, a root r, and a set of terminals S (a set of timber nodes Z), determine a directed Steiner tree T with minimum cost. Therefore, the problem is equivalent to DST. The outdegree of timber nodes in G is always 0 and hence T is the full Steiner tree. In this paper, the work processes incorporated into the problem are only skidding/yarding operations. It is easily expected that the problem is DST even if other work processes represented by edges are incorporated into the problem.

3.4 Solution algorithms

In the previous section, we showed that the problem is equivalent to DST. Thus, we can use algorithms for DST to solve the problem. Because of the NP–hardness of solving DST, we need to use heuristic algorithms to find approximate solutions in reasonable amounts of time, when solving large instances.

An approximation ratio of an algorithm, (i.e., the worst ratio between the approximate solution and the optimal solution) is of importance not only from a theoretical but from a practical perspective. There are various 2–approximation algorithms for ST [70]. In contrast, a reduction from the set cover problem strongly implies that there is no approximation algorithm for DST whose approximation ratio is better than $O(\log n)$ [47]. Because approximation ratio $O(\log n)$ is too large to make sense from a practical perspective, we make no mention of approximation ratio of DST heuristic algorithms described below.

3.4.1 Existing heuristic algorithms for DST

It is often the case that heuristic algorithms for DST derive from ones for ST, namely, heuristic algorithms for ST are adopted to solve DST [145]. First, we explain four heuristic algorithms for DST, the shortest paths with origin heuristic (SPOH), minimum spanning tree heuristic (MSTH), shortest path heuristic (SPH) and longest path heuristic (LPH), which are originally heuristic algorithms for ST and available to solve DST. These algorithm names are in accordance with those described in [70, 154]. Next, we describe the algorithm of Charikar et al. [19], which is developed exclusively for DST, and has the current best approximation ratio.

The SPOH [130] constructs a tree consisting of shortest paths from the root to all the terminals, by solving the shortest path problem once. The MSTH [130] first compute the minimum spanning tree of the graph, and secondly delete from the tree non-terminals whose outdegree is 0. The SPH [130] constructs a tree by greedily adding the closest terminal and the corresponding shortest path until the tree contains all the terminals. The procedure of the SPH is as follows.

Algorithm 1 Shortest path heuristic

1: **procedure** SPH(G, r, S)
2:     $T \leftarrow (\{r\}, \emptyset)$
3:     **for** $i = 1$ **to** k **do**
4:         Set the cost of the edges of T to 0.
5:         Compute the shortest paths from r to all terminals.
6:         $s^* \leftarrow \arg\min_{s \in S - V(T)} d_{rs}$
7:         $T \leftarrow T \cup P_{rs^*}$
8:     **end for**
9:     **return** T
10: **end procedure**

In order to determine the closest terminal from T, line 4 sets the cost of the edges of T to 0, and then line 5 computes the shortest paths from the root to all terminals. Line 6 determines the closest terminal, and line 7 adds the corresponding shortest path. The LPH [154] is almost identical to the SPH, but differs in the addition of not the closest terminal but the farthest terminal. The procedure of the LPH is as follows.

Algorithm 2 Longest path heuristic (Same as Algorithm 1 except line 6.)

5:         $s^* \leftarrow \arg\max_{s \in S - V(T)} d_{rs}$

The time complexities of the SPOH, MSTH, SPH and LPH are $O(n^2)$, $O(n^2)$, $O(kn^2)$ and $O(kn^2)$, respectively.

According to the definitions by Charikar et al. [19], the *density* of a tree $H = (V(H), E(H))$ is the average cost required to contain one terminal in H, namely, $den(H) = c(H)/k(H)$, where $c(H)$ is the sum of the costs of the edges in H and $k(H)$ is the number of terminals in H. A tree which consists of a path from the root

r to an intermediate node v, and shortest paths from v to some terminals is called a *bunch*. The algorithm of Charikar et al. is a non-trivial algorithm which is based on greedily finding minimum density bunches, followed by recursively constructing a low density tree consisting of the bunches [for details, see 19]. The time complexity is $O(n^l k^{2l})$ for any fixed integer $l > 1$.

3.4.2 Proposed heuristic algorithms

Our proposed algorithms share the following common characteristics: (i) They can be classified as tree construction algorithms that expand a subtree T of G from the root r, as with the SPOH, SPH, LPH and algorithm of Charikar et al.. (ii) They greedily add to T, a shortest path which starts from a node in T and consists of road edges, according to the minimization or maximization of some measure.

3.4.2.1 Heuristic based on density

We first propose the simple density heuristic (SDH), which is a highly simplified version of the algorithm of Charikar et al.. From a practical application perspective, the algorithm of Charikar et al. has a limitation in terms of time complexity. That is, if a fixed integer l is set to a certain number, this algorithm suffers from high time complexity, and requires unrealistic computational time. This computational limitation is attributed to the recursive procedure for determining a low density tree. In the SDH, we eliminate the recursive procedure, and instead change a graph structure to compute density, from the simple structure (bunch) to a little complex structure, which was developed in consideration of the presence of two types of edges (road edge and skidding/yarding edge) in the graph. The structure is made up of the shortest path consisting of only road edges, and a set of skidding/yarding edges whose one endpoint is included in the shortest path (Fig. 3.2), and replicates the situation where skidding/yarding operations are done using a single road without any junctions.

The SDH constructs a tree T by greedily adding the above–mentioned structure with a minimum density, until T includes all terminals. More specifically, the algorithm is described as follows.

Algorithm 3 Simple density heuristic

1: **procedure** SDH(G, r, S)
2: $T \leftarrow (\{r\}, \emptyset)$; $i \leftarrow k$
3: **while** $i > 0$ **do**
4: $H_{BEST} \leftarrow (\emptyset, \emptyset)$
5: Set the cost of the edges of T to 0.
6: Compute the shortest paths from r to all other nodes except terminals.
7: **for all** $v \in V(G) - S$ **do**
8: $H \leftarrow P_{rv}$
9: **for** $j = 1$ **to** i **do**
10: $(u^*, s^*) \leftarrow \underset{\substack{u \in V(H) \\ s \in S - V(H)}}{\arg\min}\ c_{us}$
11: $H \leftarrow (V(H) \cup \{s^*\}, E(H) \cup \{e_{u^*s^*}\})$
12: **if** $den(H_{BEST}) > den(H)$ **then**
13: $H_{BEST} \leftarrow H$
14: **end if**
15: **end for**
16: **end for**
17: $T \leftarrow T \cup H_{BEST}$; $i \leftarrow i - |S \cap V(H_{BEST})|$; $S \leftarrow S - V(H_{BEST})$
18: **end while**
19: **return** T
20: **end procedure**

In each iteration of the main while loop (lines 3–18), the following is executed. In order to determine the shortest paths from T (more precisely, any one node in T) to all other nodes except terminals, line 5 sets the cost of the edges of T to 0, and then in line 6, the shortest paths are computed. Using these shortest paths, which consist of single roads without any junctions in the structure to compute density, the structure is constructed and evaluated in line 7–16. In line 17, the minimum density structure is added to T.

Let us consider the time complexity of the SDH. The main loop executes at most k iterations, because one iteration adds at least terminal. In the main loop, the shortest path problem is solved in $O(n^2)$ time. Moreover, the outer for loop (lines 7–16) and the inner for loop (lines 9–15) run at most $n - k$ and k iterations, each. In the inner for loop, line 10 searches for an element with minimum cost among $O(kn)$ elements. Thus, the time complexity of the SDH is $O(k(n^2 + (n-k) \cdot k \cdot kn))$, i.e., $O(k^3 n(n-k))$.

3.4.2.2 Heuristic based on cost–benefit analysis

Next, we propose several heuristic algorithms based on cost–benefit analysis. Cost–benefit analysis is one group of decision–making techniques which can assist a decision maker from an economic point of view. Characteristics consistent with the analysis is a monetary comparison between benefits and costs that occur as a consequence of decision–making. Its range of application is very wide and covers a number of practical situations [16], for example, in a public policy decision with effects spanning decades and in an investment project evaluation over relatively short period of time. Two typical measures used in the analysis are a "net benefit (*benefit-cost*)" and "cost-benefit ratio (*benefit/cost*)". If the net benefit is positive or cost–benefit ratio is more than one, we normally judge that the decision–making is appropriate from an economic point of view.

When considering the cost–benefit relationship in forest road network planning, it is natural to regard road construction costs as "cost" and we first conceive of the decrease in costs incurred in timber harvesting operations as "benefit". Road construction makes timber harvesting operations more efficient by enhancing accessibility to timber resources, and more specifically reduces the skidding/yarding distance, which is known to be positively correlated with skidding/yarding costs. Thus, we can say that investment in road construction decreases timber harvesting costs and especially skidding/yarding costs.

We carry out a cost–benefit analysis on the basis of the cost–benefit relationship to solve the problem namely, DST, which we named as the net benefit heuristic 1 (NBH_1) and cost–benefit ratio heuristic 1 (CBRH_1), by a difference in a measure used in the analysis. We note that the previous studies [79, 132], where forest road networks were designed by the analysis, motivate us to propose the NBH_1) and CBRH_1.

The NBH_1 and CBRH_1 construct a tree by greedily adding the shortest path consisting of only road edges with a maximum measure, until the measure falls below the baseline (0 or 1), followed by addition of skidding/yarding edges. Below we present the procedure of the NBH_1 and CBRH_1.

Algorithm 4 Net benefit heuristic 1 and Cost–benefit ratio heuristic 1

1: **procedure** $\text{NBH}_1(G, r, S)$, $\text{CBRH}_1(G, r, S)$
2: $\quad T \leftarrow (\{r\}, \emptyset)$
3: $\quad$ **repeat**
4: $\quad\quad P_{BEST} \leftarrow (\emptyset, \emptyset)$; $bn_{BEST} \leftarrow 0$; $cbr_{BEST} \leftarrow 0$
5: $\quad\quad$ Set the cost of the edges of T to 0.
6: $\quad\quad$ Compute the shortest paths from r to all other nodes except terminals.
7: $\quad\quad$ **for all** $v \in V(G) - S$ **do**
8: $\quad\quad\quad T' \leftarrow T \cup P_{rv}$; $cost \ \leftarrow d_{rv}$; $benefit \leftarrow 0$
9: $\quad\quad\quad$ **for all** $s \in S$ **do**
10: $\quad\quad\quad\quad \dot{c} \leftarrow \min\{c_{xs} \mid x \in V(T)\}$
11: $\quad\quad\quad\quad \ddot{c} \leftarrow \min\{c_{xs} \mid x \in V(T')\}$
12: $\quad\quad\quad\quad benefit \leftarrow benefit + \dot{c} - \ddot{c}$
13: $\quad\quad\quad$ **end for**
14: $\quad\quad\quad nb \leftarrow benefit - cost$; $cbr \leftarrow benefit/cost$
15: $\quad\quad\quad$ **if** $nb > nb_{BEST}$ or $cbr > cbr_{BEST}$ **then**
16: $\quad\quad\quad\quad P_{BEST} \leftarrow P_{rv}$; $nb_{BEST} \leftarrow nb$; $cbr_{BEST} \leftarrow cbr$
17: $\quad\quad\quad$ **end if**
18: $\quad\quad$ **end for**
19: $\quad\quad T \leftarrow T \cup P_{BEST}$
20: $\quad$ **until** $nr_{BEST} > 0$ or $cbr_{BEST} > 1$
21: $\quad$ **for all** $s \in S$ **do**
22: $\quad\quad u^* \leftarrow \arg\min_{u \in V(T)} c_{us}$
23: $\quad\quad E(T) \leftarrow E(T) \cup \{e_{u^*s}\}$
24: $\quad$ **end for**
25: $\quad$ **return** T
26: **end procedure**

In each iteration of the main repeat loop (lines 3–20), the following is executed. Lines 5–6 determine the shortest paths from T to all other nodes except terminals, as with the SDH. For each shortest path, cost–benefit analysis is performed in line 7–18. In line 19, the maximum measure shortest path is added to T. After the main loop, lines 21–24 appropriately add skidding/yarding edges, because T does not contain them.

Let us consider the time complexity of the NBH_1 and CBRH_1. The main loop executes at most m iterations, because one iteration adds at least one edge. In the main loop, the shortest path problem is solved in $O(n^2)$ time. Moreover, the outer for loop (lines 7–18) and the inner for loop (lines 9–13) run at most $n-k$ and k iterations, each. In the inner for loop, line 10 and 11 search for an element with minimum cost among $O(n)$ elements. The remainder of the for loop (lines 21–24) requires $O(kn)$ time. Thus, the time complexity of the NBH_1 and CBRH_1 is $O(m(n^2 + (n-k)kn) + kn)$, i.e., $O(kmn(n-k))$.

Furthermore, we propose the net benefit heuristic 2 (NBH_2) and cost–benefit ratio heuristic 2 (CBRH_2), by enhancing the cost–benefit relationship in an analysis. The NBH_1 and CBRH_1 regard the decrease in costs incurred in timber harvesting operations as "benefit", and hence only takes account of enhancing accessibility to timber resources, using skidding/yarding edges. In contrast, through understanding that road construction makes it easier to construct further roads, the NBH_2 and CBRH_2 intend to enhance accessibility, using road edges as well as skidding/yarding edges. Thus, "benefit" is the decrease in costs incurred in both road construction and skidding/yarding operations. In the NBH_2 and CBRH_2, it is necessary to preliminarily compute a all–pairs shortest distance matrix. The difference in procedure with the NBH_1 and CBRH_1 is calculating benefit with the matrix, and then the parts to be modified are only lines 10–12 in Algorithm 4, as follows.

Algorithm 5 Net benefit heuristic 2 and Cost–benefit ratio heuristic 2 (Same as Algorithm 4, except lines 10–12.)

10: $\dot{d} \leftarrow \min\{d_{xs} \mid x \in V(T)\}$
11: $\ddot{d} \leftarrow \min\{d_{xs} \mid x \in V(T')\}$
12: $\mathit{benefit} \leftarrow \mathit{benefit} + \dot{d} - \ddot{d}$

3.5 Computational experiments

In our experiments, the performances of 7 algorithms (the SPH, LPH, SDH, NBH_1, NBH_2, CBRH_1 and CBRH_2) was investigated by solving realistic 30 problem instances. These algorithms were coded in Matlab 8.2 on a personal computer with 32 GB RAM and Intel Core i7, 3.6 GHz processor.

Because in preliminary experiments, both the SPOH and MSTH, which have the most simple procedure, were clearly inferior in terms of solution quality, and the algorithm of Charikar et al. do not terminate in real time, for our problem instances described below, these three algorithms were excluded here. Use of a mixed–integer programming solver (based on branch and bound methods) is generally an promising way of solving combinatorial optimization problems. However, under our experimental conditions, preliminary experiments showed that even in the smallest of our problem instances (described below), a state–of–art solver (ILOG CPLEX 12) ran out of memory with poor solutions and large optimality gaps, owing to its large size. Thus the solver also was excluded.

Our experiments were undertaken in 15 planning areas located in the Tsuzuki District, Kyoto, Japan (Fig. 3.4). These areas were mostly covered by managed forests for timber production, and ranged about 40 ha to 100 ha (Table 3.4). They were numbered in order of increasing area. In Japan, the Geospatial Information Authority of Japan has provided a 10 m $\times$ 10 m DEM (digital elevation model) [54]. The average terrain slope for each area was calculated using the DEM, and ranged about 20° to 35°. Considering that the terrain slope of 61 % of managed forests in Japan is between 21° and 45° [49], the areas have Japanese common terrain in terms of terrain slope. In areas around the planning areas, it is difficult that harvesting machinery such as a wheel skidder enters directly into the forests because of the steep terrain, and so two main types of harvesting machinery are actually used in skidding/yarding operations: an excavator with a winch (EW) and swing yarder (SY). The former performs winch skidding operations while the latter does cable yarding operations. Both machinery are installed only on roads. The maximum skidding/yarding distances were set to 60 m and 200 m [74]. Suppose that given each planning area, a forest engineer seeks to design road networks suitable for skidding/yarding operations performed by either EW or SY. 30 problem instances were generated for each combination of planning areas and harvesting machinery, according to the following description.

3.5.1 Problem instances

The upper part of Table 3.2 shows road design specifications for potential road networks, which were determined with reference to the Forest Road Regulations in Japan. In preliminary experiments, we found that the eight–neighbor representation could not generate potential road networks which spread all over each planning area, because under the influence of the steep terrain, road sections corresponding to the road edges often violate the restriction of the maximum road gradient, and then the potential road network was segregated. Then we employed the state–of–the–art elaborate representation developed by [126]. In this representation, road nodes are located at grid points of a 10 m $\times$ 10 m grid, every node has 48 neighbors, and a set D of possible directions contains 16 directions. Among road edges generated by this representation, we excluded those that violate the restriction of the maximum road gradient or minimum horizontal curve radius shown in Table 3.2. We regard road nodes within 10 m of existing road networks (Fig. 3.4) as existing nodes.

As a cost function ω_{road} that assigns road construction costs to road edges, we employed the cost estimation model proposed by [125]. This model, which consists of four submodels for estimating costs associated with embankment structure, pavement structure, retaining structure and drainage structure, allows an estimate of road construction costs affected by the geographic properties of road sections. The cost parameters for the model are shown in the lower part of Table 3.2.

Timber resources to be harvested were assumed to be located in the timber production stands of the areas. The stands were divided into 30 m $\times$ 30 m square grid cells with centers representing the timber nodes, where timber resources within the cell were accumulated. It was assumed that all timber nodes must be harvested and then the no–harvesting criteria α was set to sufficiently–large ($\alpha = 10^{10}$ JPY).

As for skidding/yarding edges whose one endpoint is a road node and the other one is a timber node, if the distance between the road node and timber node is more than the maximum skidding/yarding distance, the edges were removed. Moreover, if harvesting machinery is SY, that is, cable yarding operations are done, the physical feasibility of cable corridors was evaluated from the DEM, on the assumption that head and tail spars were installed on the road node and timber node, respectively (Fig. 3.3).

Table 3.3 gives a cost function ω_{sy} that assigns skidding/yarding costs to skidding/yarding edges, for each harvesting machinery. These functions include skidding/yarding distance, angle of inclination in skidding/yarding operations and timber volume as explanatory variables.

Table 3.1 presents characteristics of the generated directed graph. Redundant edges not in the connected component containing the root were removed, and hence there was at least one path from the root to every other node. The direct adoption of the elaborate representation [126] made the graph size very large compared with the previous studies shown in Table 1.1.

3.5.2 Postprocessing

To improve the tree T obtained by the heuristic algorithms, the improvement procedure noted in Rayward-Smith and Clare [103] was used, which produced an effective improvement in [144, 154]. It is originally used for ST, but able to be applied to DST. It consists of 2 steps as follows: (i) Determine a minimum spanning tree of the induced subgraph induced by $V(T)$. (ii) Remove nodes which are not terminals and whose outdegree is 0 from this minimum spanning tree. Hereafter, we will refer to the trees formed by this improvement procedure as "solutions".

3.6 Results and discussion

The maps in Fig. 3.5 show examples of the road networks designed by each heuristic algorithm. Only the SPH located clearly excess road networks. In contrast, the other algorithms seemed to do some adequate and natural networks. In general, only for harvest machinery installed only on roads (e.g., yader), the longer a maximum skidding/yarding distance of harvest machinery is, the less road networks are required, because machinery with a longer maximum skidding/yarding distance can harvest timber resources farther away from roads without road construction. In conformity with this principle, less road networks were located in SY with a longer distance. are installed on roads

3.6.1 Solution quality

We used the deviation from the best–known solution for each solution, to compare solutions obtained by the 7 algorithms in terms of solution quality.

$$dev = \frac{val - val_{best}}{val_{best}} \times 100$$

where dev is the deviation (percentage), val and val_{best} are the value of the solution for comparison and of the best–known solution, respectively. Table 3.4 gives the deviations for each problem instance and the average deviations for each harvest machinery. Figure 3.6 presents the results of multiple comparisons of the deviations for the differences in the algorithms, for each harvest machinery.

The CBRH_2 almost always outperformed all other algorithms, and then the average deviation was nearly 0. The SDH, CBRH_1 and NBH_2 gave more or less the same performance and their average deviations were around 10 %. There was no statistically significant difference among the three algorithms (Fig. 3.6). The NBH_1 had the worst performance among our proposed algorithms, which seems to be inferior to the LPH.

These experiments demonstrated that compared to the existing algorithms, our proposed algorithms except the NBH_1 tended to achieve superior solutions, namely, to design road networks that reduce the sum of road construction costs and skidding/yarding costs.

Next, we state the results of the existing algorithms (the SPH and LPH). The SPH was substantially inferior to the others, as might be expected from the shape of road networks (Fig. 3.5). By contrast, the LPH produces relatively good solutions especially in SY. The fact that the SPH was inferior to the LPH in our experiments is interesting because the opposite was observed in [154], where computational experiments were performed to investigate the performance of various heuristic algorithms for ST. This incompatibility results from the difference in graphs used in experiments. Our graphs was directed and large ($n > 6 \times 10^4, m > 10^6, k > 300$), and the obtained tree was the full Steiner tree. On the other hand, graphs in [154] is undirected and small ($n, m, k < 100$), and the terminals are not always leaves.

We should mention the inferior–to–superior relationship among the four algorithms based on cost–benefit analysis. The algorithms with cost–benefit ratio dominates those with net benefit for most problem instances (compare the NBH_1 to the CBRH_1, and the NBH_2 to the CBRH_2). The results suggest that as a measure used in cost–benefit analysis, cost–benefit ratio is more preferable than net benefit in obtaining high quality solutions. Meanwhile, the algorithms that regard decrease in not only skidding/yarding costs but also road construction costs as benefit always perform better (compare the NBH_1 to the NBH_2, and the CBRH_1 to the CBRH_2). Perhaps one of the reasons why the NBH_1 and CBRH_1 were inferior is that

The difference between the harvest machinery (EW or SY) is statistically significant for the existing algorithms and not for our proposed algorithms (Wilcoxon signed rank test; $P < 0.05$). Thus, in our experiments, there was a tendency for our algorithms to stably generate solutions regardless of harvest machinery.

3.6.2 Computational time

Table 3.5 shows the computational time required to solve each problem instance and to compute all–pairs the shortest distance matrix for each graph, which is needed to use the NBH_2 and CBRH_2. The computational time depended on the size of the graph. Because of the complicated procedures, the computational time of our proposed algorithms was several orders of magnitude longer than that of the existing algorithms. Especially, the CBRH_2 required enormous computational time where the maximum was greater than 50 hours.

3.7 Concluding remarks

The cost of road construction and timber harvesting operations fluctuate depending on road design standard, harvest machinery, and geographic conditions, but accounts for a definitely significant fraction of the total costs of timber production. The problem to design road networks minimizing the cost is an important and challenging task for forest engineers, and also contains interesting combinatorial optimization problems for operational researchers. This paper considered the problem using a graph–theoretical approach.

In our formulation of the problem, timber harvesting operations are composed of only skidding/yarding operations and do not contain other work processes. This is because of the level of detail required in planning as well as reducing problem size. We demonstrated that the problem can be formulated as DST through abstracting elements in the problem by a graph structure.

In order to solve the formulated problem, new heuristic algorithms based on density (SDH) or cost–benefit analysis (the NBH_1, CBRH_1, NBH_2 and CBRH_2) were proposed. Computational experiments were carried out to investigate the performance of our proposed algorithms. The results showed that our proposed algorithms except NBH_1 seemed to give better solutions than existing algorithms (the SPH and LPH), and CBRH_2 found the best solutions in most instances. On the other hand, our proposed algorithms are more complex from the time complexity point of view and actually took longer computational time to solve problem instances.

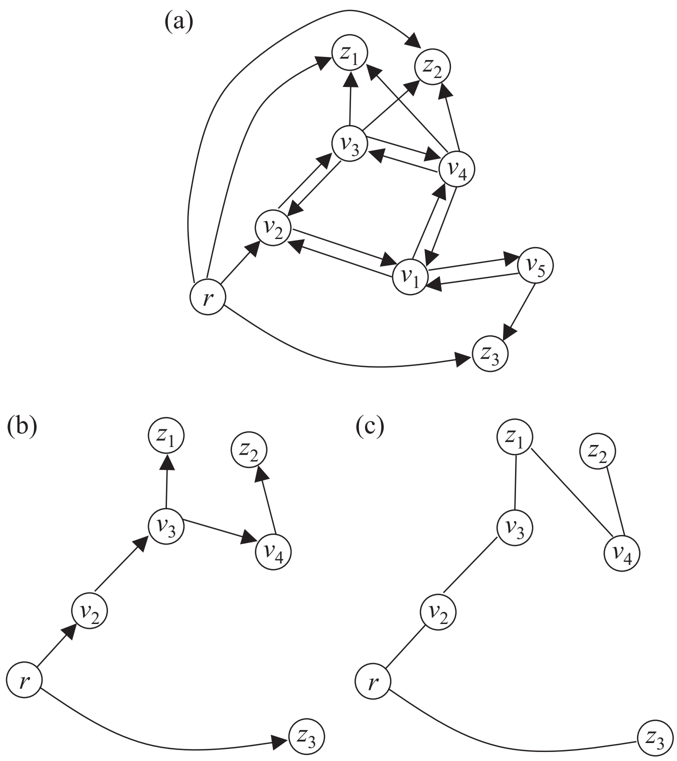

Figure 3.1: Schematic of a directed graph (a) and a Steiner tree in a directed graph (b) and in an undirected graph (c) - A root r, road nodes $v_1, v_2, v_3, v_4, v_5 \in V_{\text{road}}$, existing node $v_2 \in V_{\text{exist}}$ and timber nodes $z_1, z_2, z_3 \in Z$.

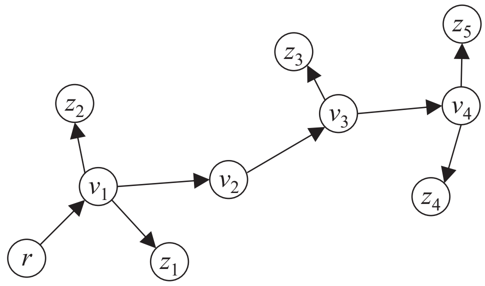

Figure 3.2: Graph structure to compute density - A root r, road nodes $v_1, v_2, v_3, v_4 \in V_{\mathrm{road}}$ and timber nodes $z_1, z_2, z_3, z_4, z_5 \in Z$.

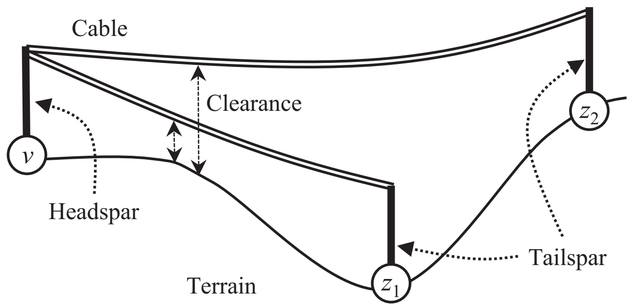

Figure 3.3: Feasibility analysis of cable corridors - Road nodes $v \in V_{\mathrm{road}}$ and timber nodes $z_1, z_2 \in Z$.

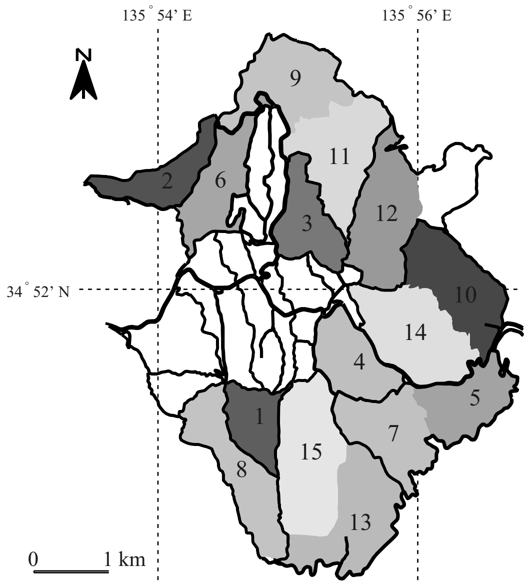

Figure 3.4: Map showing the 15 planning area - The black line indicates the existing road network.

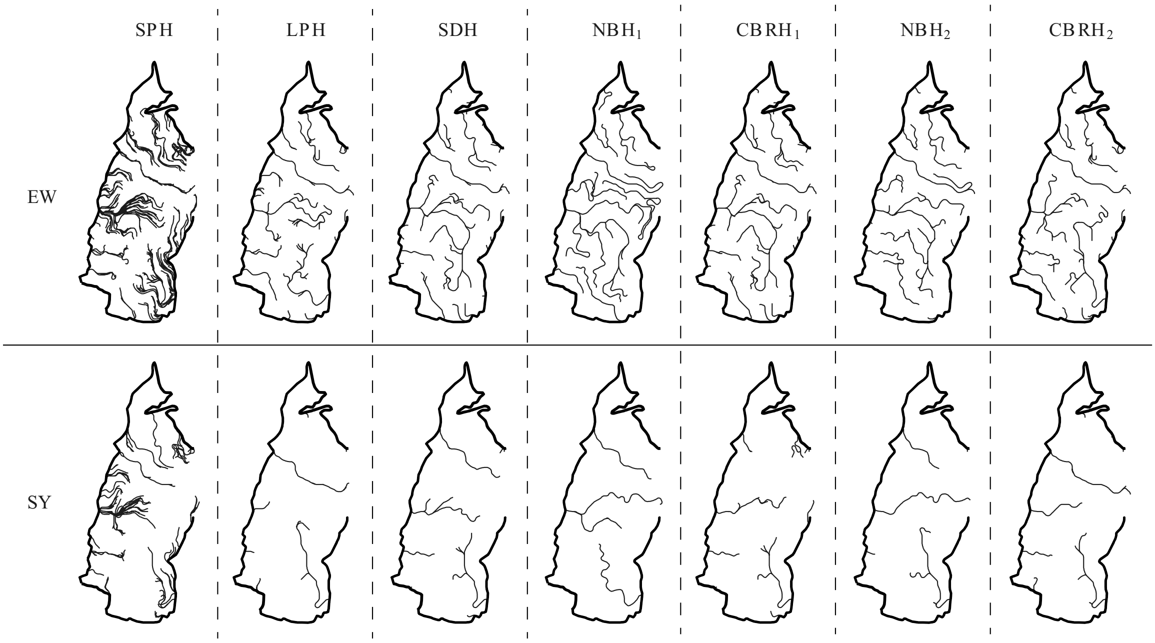

Figure 3.5: Example of the proposed road networks (Planning area No. 12) - The thin line indicates the proposed road network.

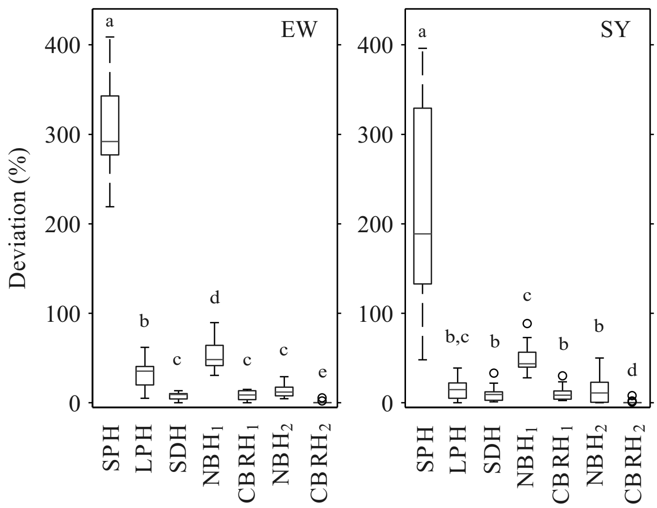

Figure 3.6: Box and whisker plot - Box and whisker plots showing median, quartiles, and extreme values for deviations (percentage) from best-known solutions. Outliers are represented by circles. Boxes labeled with different letters are significantly different, while boxes labeled with same letters are not significantly different (Kruskal–Wallis test followed by multiple comparisons using Steel–Dwass test: $P < 0.05$)

Table 3.1: Characteristics of the planning areas and the directed graphs derived from the areas.

Area No.	Area (ha)	Avg. slope (degree)	$\lvert V_{\mathrm{road}} \rvert$	$\lvert Z \rvert$	$\lvert E_{\mathrm{road}} \rvert$	$\lvert E_{\mathrm{har}} \rvert$	
						EW	SY
1	40.1	33.4	61655	387	563882	500634	2031914
2	45.6	22.6	72300	432	1581466	690698	2657119
3	52.2	28.6	81374	507	1175694	744030	2898786
4	55.0	27.7	86477	322	1457037	495022	1887659
5	56.5	28.4	89233	488	1222028	729840	3334980
6	59.3	20.2	94583	553	2422830	883315	4173863
7	68.3	34.2	106167	674	899414	888609	3774593
8	76.5	33.3	118772	762	1080838	1006300	4608123
9	78.1	31.7	115387	746	1537825	946596	4183811
10	79.5	27.5	124836	792	2028939	1191801	4633452
11	84.7	30.3	130927	919	1746227	1296957	5616333
12	86.9	28.9	135568	861	1748612	1276482	5361198
13	87.4	29.3	129061	855	1954626	1195076	5323560
14	91.8	30.7	144245	844	2018741	1202858	4902337
15	100.0	31.9	151762	977	1877508	1340064	6146723

Table 3.2: Road design specifications and road construction cost parameters.

Parameter (Units)	Value
Maximum road gradient (%)	14
Minimum horizontal curve radius (m)	12
Maximum deflection angle of horizontal curve (°)	180
Standard road surface width (m)	3
Additional width for ditch and shoulder (m)	0.5
Cut–slope angle	1:0.6
Fill–slope angle	1:1.5
Excavation cost per volume unit (JPY/m^3)	450
Compaction cost per volume unit (JPY/m^3)	400
Cost for pavement structures (JPY/m^2)	2000
Cost for retaining walls (JPY/m^2)	4000
Cost for drainage structures (JPY/m)	2000

Table 3.3: Cost function ω_{sy} for skidding/yarding edges [74]. The function of dis_{vz}, θ_{vz} and vol_z calculates skidding/yarding cost (JPY) incurred in skidding/yarding a timber node $z \in Z$ by a machinery in a road node $v \in V_{\mathrm{road}}$, where dis_{vz} and θ_{vz} are the distance (m) and the angle of inclination (°) from v to z, respectively, and vol_z is the timber volume (m^3) of z.

Machinery	Function
EW ($dis_{vz} \leq 60$ m)	$\omega_{\mathrm{sy}} = \begin{cases} \left(5.88 \times dis_{vz} \times \left(\mathrm{e}^{0.031 \times \theta_{vz}} + \mathrm{e}^{0.042\theta_{vz}+0.42}\right) + 359.9\right) \times vol_z & \text{if } \theta_{vz} \geq 0, \\ \left(5.88 \times dis_{vz} \times \left(\mathrm{e}^{0.035 \times \theta_{vz}} + \mathrm{e}^{0.053\theta_{vz}+0.42}\right) + 359.9\right) \times vol_z & \text{if } \theta_{vz} < 0. \end{cases}$
SY ($dis_{vz} \leq 200$ m)	$\omega_{\mathrm{sy}} = \begin{cases} \left(5.29 \times dis_{vz} \times \left(\mathrm{e}^{0.0035 \times \theta_{vz}} + \mathrm{e}^{0.0050\theta_{vz}+0.27}\right) + 1441.9\right) \times vol_z & \text{if } \theta_{vz} \geq 0, \\ \left(5.29 \times dis_{vz} \times \left(\mathrm{e}^{0.0030 \times \theta_{vz}} + \mathrm{e}^{0.014\theta_{vz}+0.27}\right) + 1441.9\right) \times vol_z & \text{if } \theta_{vz} < 0. \end{cases}$

Table 3.4: Deviation (percentage) from best–known solutions.

Machinery	Area No.	SPH	LPH	SDH	NBH_1	$CBRH_1$	NBH_2	$CBRH_2$
EW	1	314.8	40.8	10.1	51.6	4.2	13.0	0.0
	2	219.2	39.3	3.9	56.6	0.1	5.2	0.0
	3	250.4	54.5	9.4	66.5	8.8	12.0	0.0
	4	298.9	39.6	10.3	78.4	14.1	7.7	0.0
	5	367.6	61.9	7.6	30.8	6.7	11.5	0.0
	6	277.7	5.1	5.6	39.3	1.4	18.0	0.0
	7	395.7	18.0	11.4	38.9	9.1	4.8	0.0
	8	286.4	7.2	0.0	40.5	3.4	4.6	2.0
	9	269.6	26.3	1.9	57.5	0.9	25.9	0.0
	10	352.4	11.1	9.7	44.6	11.3	15.9	0.0
	11	288.0	35.3	13.5	66.6	13.6	24.3	0.0
	12	276.7	50.2	6.1	89.5	7.2	8.5	0.0
	13	292.0	36.1	12.3	48.4	13.7	29.3	0.0
	14	295.2	29.6	9.4	47.1	13.3	12.0	0.0
	15	408.8	33.3	0.0	46.6	15.0	12.6	5.7
	Avg.	306.2	32.6	7.4	53.5	8.2	13.7	0.5
SY	1	259.8	3.1	22.1	40.6	23.6	0.0	8.0
	2	85.0	21.3	9.3	33.5	8.6	4.3	0.0
	3	157.7	14.8	5.7	28.1	3.3	11.0	0.0
	4	124.4	10.1	12.8	47.6	13.3	1.2	0.0
	5	187.1	2.2	9.3	72.9	10.6	50.0	0.0
	6	48.1	25.0	1.1	39.3	2.7	37.5	0.0
	7	184.2	7.8	15.8	39.7	13.0	0.0	2.1
	8	48.5	4.3	1.3	57.3	3.9	0.2	0.0
	9	282.2	22.1	1.7	88.7	3.7	0.0	0.9
	10	396.2	0.0	2.0	43.5	4.6	14.6	0.2
	11	350.5	22.1	33.0	66.1	30.1	28.8	0.0
	12	289.6	7.7	10.6	40.3	18.4	14.8	0.0
	13	188.9	25.2	8.7	40.5	6.2	25.5	0.0
	14	357.5	22.2	8.7	54.3	7.3	8.0	0.0
	15	342.6	38.9	10.0	51.0	11.9	15.8	0.0
	Avg.	220.2	15.1	10.1	49.6	10.7	14.1	0.7

Table 3.5: Computational time (seconds) to solve each problem instance and to create the all–pairs shortest distance matrix.

Machinery	Area No.	SPH	LPH	SDH	NBH_1	$CBRH_1$	NBH_2	$CBRH_2$	Shortest distance matrix
EW	1	0.7	1.8	357.0	23.6	110.4	979.6	4629.2	765.9
	2	1.5	2.6	619.4	53.8	157.6	3550.7	22007.3	1694.0
	3	2.0	4.6	864.5	59.8	279.5	4000.8	24810.5	1832.0
	4	1.5	5.0	531.7	55.6	200.5	2250.7	14683.5	2033.7
	5	2.2	6.0	889.9	70.4	310.9	4296.1	27035.3	2064.1
	6	2.7	6.7	1276.5	83.2	382.5	8327.6	66474.4	3508.1
	7	3.7	9.2	1749.6	121.9	738.9	8421.0	53709.4	2282.1
	8	3.6	9.4	2330.7	142.0	919.5	11609.4	79689.3	2940.4
	9	4.4	10.2	2793.9	146.2	1080.8	10905.1	130491.8	3748.5
	10	5.9	11.6	2628.2	212.3	1249.1	15602.8	146435.9	6041.4
	11	6.0	11.5	4058.8	221.0	1338.3	18440.2	192648.5	4867.3
	12	6.5	15.0	3490.9	309.7	1804.2	21367.1	205629.8	4284.0
	13	5.8	14.9	2253.5	205.8	1093.0	15958.1	141659.7	3875.4
	14	5.5	17.3	4146.5	238.7	1541.4	17601.4	185357.9	4909.0
	15	9.3	21.7	4616.3	507.2	3034.8	23192.2	196126.8	5019.1
SY	1	1.2	1.8	145.7	9.3	30.5	508.7	923.7	2674.5
	2	1.7	4.0	205.4	14.0	44.8	1185.0	3409.7	4840.8
	3	2.1	3.8	330.6	19.0	59.9	1686.6	3479.5	5274.1
	4	1.6	2.9	374.1	14.5	112.3	819.5	5866.2	4738.6
	5	2.3	4.7	450.1	26.5	132.9	1822.1	5869.8	6613.9
	6	2.9	6.8	406.3	29.3	87.4	3103.9	8973.8	9810.2
	7	3.6	6.9	1009.8	47.0	311.0	2671.1	19178.9	7723.5
	8	4.3	7.1	1074.2	51.8	226.8	3783.4	10081.2	10352.0
	9	5.0	7.3	871.3	53.4	228.2	3889.3	34231.1	9630.3
	10	5.6	11.0	1028.1	84.4	323.8	6817.5	37390.6	14020.1
	11	7.2	10.6	1744.8	87.1	544.9	5269.7	31094.8	16697.4
	12	6.1	13.2	1054.6	94.7	350.8	7491.5	35147.9	16191.2
	13	4.3	6.0	1141.7	65.0	271.1	6340.5	31349.0	15501.1
	14	7.8	12.7	2231.5	166.4	674.7	7851.2	43635.5	16740.9
	15	8.4	17.4	2080.3	193.1	1164.4	7322.4	59544.7	18778.5

4

Cable corridor layout problem in cable yarding operations: Formulation and solution using graph theory

4.1 Introduction

Cable yarding technology has long been an indispensable tool for timber harvesting operations [64, 111]. The technology is especially beneficial in countries and regions where large areas are covered by mountain forests, such as Japan, Central Europe, and the Pacific Northwest in North America. On such steep terrains, ground-based systems (e.g. crawler tractors and wheeled skidders) are rendered impractical. In addition, cable yarding systems cause less soil disturbance and compaction than ground-based systems [83, 89, 129]. Ecological efficiency of cable yarding systems is particularly desirable in the current drive to minimize the environmental impact of logging operations [141].

However, when using cable yarding systems, logging planners must address the challenging task of designing a cable corridor layout (CCL) before operations begin. The time horizon of operational planning, during which the specific geometry of corridors and landings is designed, is from one week to a few months [30]. In most simple terms, logging planners must determine whether a fan-shaped or parallel corridor pattern is more appropriate (Fig. 4.1). Simultaneously, they should evaluate whether each timber stand can be yarded within the physical, economical, and environmental limits. Indeed, CCL largely determines the success of cable yarding operations. The basic elements of the layout (e.g. location, number and length of corridors) exert a major effect on the economic and environmental effectiveness of these operations [29, 30, 65].

CCL design is rendered difficult by two main factors: (*i*) Timber stands are distributed non-uniformly across the terrain and vary significantly in timber quality and quantity, and (*ii*) Logging planners must decide among many layout alternatives in order to optimize objectives, such as maximizing total profit. The former complicates logging feasibility evaluation of the timber stands. The latter determines the placement of forest harvesting equipment and forms the basis of forest management planning at the operational level [119]. In this study, designing a CCL at maximum profit is denoted as the CCL problem. Owing to the combinatorial nature of the design process, the CCL constitutes a combinatorial optimization problem, which is notoriously difficult to solve. Once solved, the challenging task of finding an optimal layout remains. Among the software packages designed for CCL are PLANS [142] or Cable Analysis [23], which evaluates layout alternatives. As a group, these packages estimate the physical feasibility of cable corridors or the yarding costs. Given sufficient digital terrain and forest cover data, they greatly facilitate CCL design, but cannot automatically design an optimal CCL.

In a pioneering study of the optimal layout problem, Dykstra [37] formulated CCL using an integer programming approach, and developed a heuristic solution algorithm. His formulation was inspired by an analogy between CCL and a well-known combinatorial optimization problem termed the location-allocation problem (LA). The LA seeks to locate multiple facilities that must service a set of customers at minimum cost, given that each facility is established at fixed cost and that each shipment from the facility to the customer incurs a transportation cost. Dykstra showed that the one-to-many relationship between facilities and customers is similar to that between cable corridors and timber to be yarded. That is, the allocation of timbers to corridors in CCL is analogous to the allocation of customers to facilities in LA.

The analogy between CCL and LA is superficially natural. Nevertheless, CCL cannot be directly transformed into LA because the number of steps required for service delivery differs between the two cases. In LA, facilities are established to serve customers in a single step, whereas timber yarding implemented in CCL requires two steps:

the construction of log landings near roadsides, followed by the installation of cable corridors from the constructed landings. Another limitation of this formulation is that all timber stands within a planning area are assumed yarded. This activity would likely decrease the profit even if the harvested volume increases, because the unprofitable stands are always harvested. Logging planners must manually delete the timber stands they regard as uneconomical.

For a single cable corridor, a major consideration is the optimal placement of intermediate supports between the head and tail spars. Sessions [115] developed an elimination heuristic to minimize the number of intermediate supports [for details, see 23]. Leitner et al. [85] addressed the optimal location of intermediate supports using graph theory. They showed that this problem can be transformed to the shortest path problem on a directed graph. Candidate points, such as the head spar, tail spar, and intermediate supports, are considered as nodes of the graph. An arbitrary pair of nodes is connected by a directed edge extending from the head spar to the tail spar. The directed edges represent cable corridor spans, which form parts of the single cable corridor. The formulation of Leitner et al. [85] was recently adopted by Bont and Heinimann [14] to investigate how intermediate support location depends on cable structural analysis.

A well-studied forest harvesting problem involves the simultaneous harvesting machinery placement and forest road construction [3, 15, 24, 41, 84]. The time horizon and planning area of the harvesting problem frequently exceeds that of CCL. Moreover, the above-mentioned studies did not focus on a detailed CCL, although CCL may be regarded as a sub-problem [24, 41]. Thus, the methods adopted in these studies are not directly applicable to CCL. Furthermore, neither optimum road spacing of cable yarding operations [57, 63, 68] nor optimum landing location [28, 58, 59, 98] provide an optimum CCL.

The aim of this study is to re-formulate and solve the CCL problem. Unlike the previous formulation of Dykstra [37], unprofitable stands are not harvested in our formulation, enabling more profitable layout alternatives. Additionally, because the formulation is based on standard graph theory, it can adopt existing approximation algorithms. Using our approach, we aim to design detailed CCLs. The results may significantly aid the automatic or computer-aided design of CCLs.

The remainder of this paper is as follows. First, we introduce basic concepts of graph theory that are relevant to our approach. Second, we describe the details of CCL and present a novel formulation based on graph theory. We demonstrate that CCL can be transformed to the k-directed Steiner tree (DST) problem. Third, we apply two existing approximation algorithms for solving CCL (those of 130 and 19). The performance of both the algorithms is assessed by computational experiments. Finally, conclusions and directions for future research are presented.

4.2 Methods

4.2.1 Graph theory preliminaries

Let $G = (V, E)$ be a weighted directed graph comprising a set $V = \{v_1, \dots v_{|V|}\}$ of nodes and a set $E = \{(v_i, v_j)|v_i, v_j \in V\}$ of directed edges, where $|V|$ denotes the number of nodes in V. A directed edge $(v_i, v_j) \in E$ represents a directed connection from a node v_i to a node v_j. A edge weight $w(v_i, v_j)$ is assigned to each edge $(v_i, v_j) \in E$.

A *path* is a sequence of edges. In contrast, a *cycle* is a path that starts and ends at the same node. A *directed acyclic graph* (DAG) is a cycle-free directed graph. A *directed tree* D is a directed graph with the following properties: D contains a single special node called the *root*, no edges enter the root, and a single path exists from the root to every node. A *leaf* of D is a node attached to a single edge, while the number of edges in the path defines the path *length*. The *level* of a node u in D is the length of the path from the root to u. In an i-*level tree*, no leaf resides more than i edges from the root. Let $V(G)$ denote the node set of the graph G. A graph H is referred to as an *induced subgraph* of G if $V(H) \subseteq V(G)$ and the edge set of H is the set of all edges in G connecting two nodes in $V(H)$.

A fundamental combinatorial optimization problem in graph theory is the *DST* problem, which has been extensively applied to network design [35]. In DST, we are given a weighted directed graph $G = (V, E)$, a set $S \subseteq V$ of nodes called *terminals*, and a root r. DST aims to find a minimum weight tree rooted at r that includes all terminals in S, and the tree's weight is the sum of the weights of the edges in the tree. This tree is termed the Steiner minimum tree. The DST is NP-hard [70], implying that an efficient exact algorithm for DST probably does not exist. Charikar et al. [19] formulated the k-*DST* as a generalization of DST. The k-DST seeks a minimum weight tree rooted at r that includes at least k terminals in S, where k is a given positive integer, $k \leq |S|$.

4.2.2 The CCL problem

4.2.2.1 Basic elements of cable yarding systems and operations

All cable yarding systems contain the same essential structural components (Fig. 4.2). Yarding equipment such as the yarder, carriage, head spar, tail spar, and cable determines the maximum chord length of a cable corridor and the maximum lateral yarding distance. The ground clearance, defined as the distance between corridor and terrain, must exceed a specified minimum. Regardless of design, for example, whether the skyline design is running or standing, all cable yarding systems operate by transporting timber from stump to landing along a cable corridor suspended between the head and tail spars. To incorporate the versatility of cable corridor designs, our study conforms to the operating essentials, and makes no specific assumption about cable yarding systems. However, for simplicity, we also assume that no intermediate support is required. Optimal placement of intermediate supports remains an open-ended problem, even in a single cable corridor [14].

Cable yarding operations are broadly classified into three operational processes: (1) *Landing construction.* Log landings are constructed close to roadsides, enabling efficient unloading of timber from carriages and logs onto trucks. (2) *Cable installation and removal.* A cable corridor is installed prior to timber yardings, and removed afterwards. The yarder and head spar are erected near or within the landing, while the tail spar is erected within the stand. The presence or absence of this process distinguishes cable yarding system from ground-based system. (3) *Timber yarding.* During repetitive timber extraction, a carriage travels back and forth between a landing and each corridor position that is close to deposited timber. A hierarchical relationship exists among these three processes. Landing construction permits multiple cable installations (leading to fan-shaped patterns) at the constructed landing, while cable installation enables repetitive timber extraction along the installed cable corridor.

4.2.2.2 Informal description of the problem

The formulation of CCL as a combinatorial optimization problem on a graph is informally described as follows: CCL depends on the stand, the terrain and road conditions, and the technical specifications for yarding equipment. During this process, the logging planner attempts to maximize the total profit, calculated as the income from the yarded timber minus the cost of the above three operational processes. Crucially, the planner seeks to eliminate unprofitable stands from the operations, regardless of whether these stands can be physically yarded. Thus, the designed CCL frequently contains non-yarded timber stands.

4.2.2.3 Abstraction of cable yarding operations

Cable yarding operations are extracted using a weighted directed graph $G = (V, E)$. The node sets and edge sets of this graph are defined as follows.

- r root
- L set of landing nodes representing candidate landings; $L = \{l_1, \ldots, l_{|L|}\}$
- C set of cable nodes representing candidate cable corridors; $C = \{c_1, \ldots, c_{|C|}\}$
- Z set of timber nodes representing timber sources; $Z = \{z_1, \ldots, z_{|Z|}\}$
- E_L set of landing construction edges associated with a landing construction cost (negative value); $E_L = \{(r, l_i)|l_i \in L\}$
- E_C set of cable installation edges associated with a cable installation and removal cost (negative value); $E_C = \{(l_i, c_j)|l_i \in L, c_j \in C\}$
- E_Z set of yarding edges associated with a timber income minus a timber yarding cost; $E_Z = \{(c_i, z_j)|c_i \in C, z_j \in Z\}$

To visualize the transformation of cable yarding operations into a graph structure, we consider the situation in Fig. 4.3a. Candidate landings, candidate cable corridors, and timber sources within a planning area are considered as nodes. The graph G contains all these nodes plus a root node. The three operational processes are regarded as weighted directed edges: where "landing construction," "cable installation and removal," and "timber yarding" edges connect the root to landing nodes, landing nodes to cable nodes, and cable nodes to timber nodes, respectively.

All cable corridors in C ensure physical feasibility within limitations such as minimum ground clearance. The edge set E_C contains only edges from $l_i \in L$ to $c_j \in C$ of which the head spar is installed on or near l_i, while the edge set E_Z contains only edges from $c_i \in C$ to $z_j \in Z$ within the yarding area of c_i, which is determined by a cable corridor itself and maximum lateral yarding distance (Fig. 4.4). All timber nodes in Z can be yarded by at least one cable corridor in C. In other words, at least one yarding edge enters each timber node. The situation of Fig. 4.3a is equivalent to the directed graph G shown in Fig. 4.3b.

The structure of G is highly specialized. In particular, no cycle exists in G; hence G is a DAG, and a path from the root to an arbitrary node is uniquely determined. Edges exist solely between specific pairs of node sets ($\{r\}$ and L, L and C, L and T).

Once the graph has been constructed, weights corresponding to the income and/or costs associated with each process are assigned to each edge type. We assume that a timber node cannot generate income until the process “timber yarding” is completed. Thus, the income is assigned solely to yarding edges.

To simulate elimination of unprofitable timber stands from cable yarding operations, we introduce an arbitrary positive integer $k(\leq |Z|)$ as the number of timber nodes to be yarded in the currently projected operations. The integer k accounts for conditions in which all timber nodes in a planning area are not always yarded. More specifically, k timber nodes are to be yarded, leaving $|Z| - k$ timber nodes non-yarded. In this way, potentially unprofitable timber nodes are eliminated from the currently projected operations by adjusting the parameter k.

4.2.2.4 Formulation of the problem

Based on the above descriptions, we formally define CCL on a graph as

- *Given:* A weighted directed graph $G = (V, E)$, where $V = \{r\} \cup L \cup C \cup Z$ and $E = E_L \cup E_C \cup E_Z$, and a positive integer $k \leq |Z|$.
- *Find:* A maximum weight tree T rooted at r that includes at least k timber nodes in Z.

The sum of edge weights in T equals the total profit of cable yarding operations serving at least k timber nodes; hence, the tree T represents an optimal (most profitable) CCL. Moreover, T is a 3-level tree with all leaves located at level 3 indicating that yarded timber is transported through the three processes. Figures 4.3c and 4.3d shows the optimal solution of CCL (Fig. 4.3b) when $k = 5$ and $k = 4$, respectively. Whereas the formulation of Dykstra [37] deals with the former case only ($k = |Z|$), our formulation treats both cases ($k \leq |Z|$). This feature leads to higher profitability: For example, if cable yarding operations of z_3 generate little income and incur a high cost, the layout shown in Fig. 4.3d is more economically viable than that in Fig. 4.3c. Edge directionality, which denotes the hierarchical relationship between the processes, provides a feasible layout. Absence of edge directionality will yield an infeasible layout (Fig. 4.3e). It should be noted that the integer k is not a decision variable in this optimization problem, but is determined by the logging planner from various perspectives while reviewing the plan. Deciding the optimal value of k, which depends on the preference of logging planners, is outside the scope of this study.

The CCL on a graph can be easily transformed to k-DST: Without loss of generality, the maximization problem CCL is converted to a minimization problem by multiplying the edge weights by -1. A set Z of timber nodes plays the same role as a set of terminals. An optimal solution to this minimization problem is a minimum weight tree spanning at least the required number of terminals, which equates to an optimal solution of k-DST. Hence solving CCL on a graph is equivalent to solving k-DST.

4.2.2.5 Edge weight calculation

To design an operable CCL, we assign appropriate edge weights to the three different types of edges in the input graph of CCL. Here, we present a simple method for calculating the edge weights, that is, the income and cost of each process.

The construction cost λ of one landing, which is assumed constant, is assigned to each landing construction edge.

$$w(r, l_i) = -\lambda \quad \forall (r, l_i) \in E_L, l_i \in L \tag{4.1}$$

As is well-known, cable installation and removal costs are positively correlated with chord length of the cable corridor [123]. Therefore, we assume that cost increases linearly with increasing chord length to each cable installation edge:

$$w(l_i, c_j) = -(\mu_1 \times d_{c_j}^{\mathrm{cho}} + \mu_2)$$
$$\forall (l_i, c_j) \in E_C, l_i \in L, c_j \in C \tag{4.2}$$

where $d_{c_j}^{\mathrm{cho}}$ is the chord length (slope distance) of a cable corridor c_j (Fig. 4.4), μ_1 is the cost per unit length of installing and removing a cable corridor, and μ_2 is the fixed cost for installing and removing a cable corridor independent of cable length.

The main drivers of timber yarding cost are yarding distance, lateral yarding distance, and log volume [56, 69]. Our method calculates timber yarding costs in terms of yarding cycles that embody the effect of these three factors. The edge weight assigned to each yarding edge equals the timber income minus the timber yarding cost:

$$w(c_i, z_j) = vol_{z_j}^{\mathrm{tot}} \times \left(inc_{z_j} - \frac{\nu_1 \times d_{c_i,z_j}^{\mathrm{yar}} + \nu_2 + \nu_3 \times d_{c_i,z_j}^{\mathrm{lat}} + \nu_4}{vol_{z_j}^{\mathrm{ind}} \times num} \right)$$
$$\forall (c_i, z_j) \in E_Z, c_i \in C, z_j \in Z \tag{4.3}$$

where $vol_{z_j}^{\mathrm{tot}}$ is the total volume of a timber node z_j; $vol_{z_j}^{\mathrm{ind}}$ is the average volume per log of a timber node z_j; inc_{z_j} is the income per volume of a timber node z_j; num is the number of yarded logs per yarding cycle; $d_{c_i,z_j}^{\mathrm{yar}}$ is the yarding distance (slope distance) of a timber node z_j when using a cable corridor c_i; $d_{c_i,z_j}^{\mathrm{lat}}$ is the lateral yarding distance (horizontal distance) of a timber node z_j when using a cable corridor c_i (Fig. 4.4); ν_1 and ν_2 are the cost per unit distance and the fixed cost per yarding cycle, respectively, of yarding timber along a cable corridor; ν_3 and ν_4 denote the cost per unit distance and the fixed cost per yarding cycle, respectively, of yarding timber laterally.

4.2.3 Solution algorithms for CCL

In the previous section we demonstrated that an optimal solution of CCL can be obtained by solving k-DST. Consequently, algorithms for k-DST are applicable to CCL.

The k-DST itself is difficult to solve (NP-hard). In addition, because the number of constraints grows exponentially with problem size [21], large problems are intractable even when a commercial integer linear programming solver is used. For these reasons, several approximation algorithms for k-DST have been developed in graph theory. In general, an α-approximation algorithm is a real (polynomial) time algorithm that guarantees a solution with weight at most α times less than the optimal solution. The term α is the approximation ratio of the approximation algorithm. Approximation algorithms differ from metaheuristic algorithms in that performance is guaranteed.

In this study, CCL is solved by two representative approximation algorithms. In the first algorithm, introduced by Takahashi and Matsuyama [130], the approximation ratio equals k in k-DST. This algorithm is generally applied to the undirected Steiner minimum tree problem rather than to DST or k-DST. Another is the algorithm of Charikar et al. [19], which, to date, generates the best approximation ratio for k-DST ($\alpha = i(i-1)k^{1/i}$ for a level parameter $i > 1$). Since an optimal solution T of CCL is a 3-level tree, we set $i = 3$ to yield an approximation ratio of $6k^{1/3}$.

Because both algorithms seek the shortest (minimum weight) path, they require positive edge weights. The shortest path problem may become unsolvable if negative weights are introduced [1]. However, the shortest path in a DAG is readily found, regardless of weight sign [40]. Therefore, CCL is solvable by these algorithms when the input graph is a DAG with negative weights.

Details of these algorithms are described below. For convenience, CCL is converted to a minimization problem by multiplying the edge weights by -1.

4.2.3.1 The Takahashi–Matsuyama (TM) algorithm

The TM algorithm constructs a tree T by greedily adding the closest terminal and the corresponding shortest path until k terminals are included in T.

When using this algorithm to design a CCL, the logging planner successively selects the most profitable timber node in the current situation until the required number of yarded timber nodes is reached. A formal outline of the TM algorithm in CCL is provided in Algorithm 1.

Algorithm 6 The Takahashi–Matsuyama algorithm

$T \leftarrow \{r\}$
for $j = 1$ to k **do**
    Compute shortest paths from nodes in T to nodes in Z
    Determine the node $z \in Z$ closest to T
    Add to T the shortest path to z
    $Z \leftarrow Z - \{z\}$
end forreturn T

4.2.3.2 The Charikar' algorithm

In the algorithm proposed by Charikar et al. [19], which we call the Charikar's algorithm in this paper, a *bunch* is a tree consisting of a path from the root to an intermediary node u, followed by the shortest paths from u to the specified terminals. The *density* of a tree T, $d(T)$, is defined as follows:

$$d(T) = w(T)/n(T) \tag{4.4}$$

where $w(T)$ is the sum of edge weights in T and $n(T)$ is the number of terminals contained in T. We can interpret $d(T)$ as the average weight required for connecting a single terminal to T. The Charikar's algorithm recursively stores a minimum density bunch in each iteration until sufficient terminals are contained.

In applying this algorithm to CCL, the node set of a bunch comprises a root, a landing node, a cable node, and several timber nodes (Fig. 4.5). This characteristic bunch results from the special structure of the input graph of CCL. The density $d(T)$ represents the average profit per timber node. Thus, in each iteration, the algorithm stores a bunch of the three processes yielding the highest average profit.

The Charikar's algorithm was originally formulated using a recursive representation. However, noting the restricted structure of a bunch in CCL, we adopt the algorithm outlined in Algorithm 2.

Algorithm 7 The Charikar's algorithm

```
T ← ∅
while k > 0 do
    T_BEST ← ∅
    d(T_BEST) ← ∞
    for each node c ∈ C do
        Z′ ← nodes in Z adjacent to c
        for k′ = 1 to |Z′| do
            Choose k′ edges connecting c to nodes in Z′ in ascending order of edge weights
            Construct a bunch T′ of the k′ edges and the path from r to c
            if d(T_BEST) > d(T′) then
                T_BEST ← T′
            end if
        end for
    end for
    T ← T ∪ T_BEST
    k ← k − |Z ∩ V(T_BEST)|
    Z ← Z − V(T_BEST)
end whilereturn T
```

4.2.3.3 Improvement of the solution

Next, we seek to improve the solution T obtained by the above algorithms. The improvement procedure of Rayward-Smith and Clare [103] finds a minimum spanning tree of the induced subgraph induced by $V(T)$ and deletes leaves that are not terminals (in our case, terminals are timber nodes) from this tree. The resulting processed spanning tree is the improved solution. A minimum spanning tree in a directed graph is computed by a polynomial algorithm such as the Edmonds algorithm [38].

4.3 Computational experiments

We performed computational experiments in which the CCLs designed by the two algorithms were evaluated on real-time data. Our approach including all algorithms and functions (such as the cost computed function and the cable feasibility judging function) were implemented in MATLAB Version R2012a and the experiments were run on an Intel Core i7 processor running at 3.6 GHz with 16 Gbyte RAM.

4.3.1 Problem instances and parameter values

The experimental site was a forest management unit (268.4 ha) dominated by planted coniferous trees in Takayama City, Gifu Prefecture, central Japan (lat 36°02′ N, long 137°21′ E) (Fig. 4.6a). A 2-by-2-m digital terrain model (DTM) from LiDAR data is available for the entire Gifu Prefecture. The site had a mean gradient of 47.6% as a result of calculation using the DTM. Because of the steep terrain, the use of cable yarding systems appeared to be the most preferred choice for harvesting timber from the site. The GIS layers of the site included tree species distribution, average volume per log and total volume per hectare of each timber stand. The planted tree species were Japanese cypress (*Chamaecyparis obtusa*), Japanese larch (*Larix leptolepis*) and Japanese cedar (*Cryptomeria japonica*) (Fig. 4.6b).

In our computational experiments, we assumed the use of a mobile tower yarder with the parameter values listed in Table 4.1. The cost parameters were set as follows: $\lambda = 200,000$ (JPY); $\mu_1 = 40.0$ (JPY/m); $\mu_2 = 15,726.7$ (JPY); $\nu_1 = 4.3$ (JPY/m); $\nu_2 = 390.4$ (JPY); $\nu_3 = 44.9$ (JPY/m); and $\nu_4 = 45.2$ (JPY). The values of μ_1 and μ_2 were estimated from time analyses of cable installation and removal operations reported by Nakayama and Hashira [94], while ν_1, ν_2, ν_3 and ν_4 were estimated from reports of cable yarding operations by Sakurai [109]. The yarders surveyed in both analyses were mobile tower yarders operated in Japan. The timber prices for Japanese cypress, Japanese larch, and Japanese cedar were assumed to be 12,000, 9,000 and 8,000 (JPY/m^3), respectively.

Figure 4.7 illustrates the generation of landing nodes and timber nodes. Candidate landings (namely, landing nodes) were erected on the road network at 10 m intervals. Meanwhile, timber sources to be yarded were assumed to be located in the timber production stands of the site. The stands were divided into 10-by-10-m grid cells with centers representing the timber nodes, where felled timber within the cell was accumulated. Tree species, average volume per log, and total volume attributes extracted from the GIS layers were added to the timber nodes. Head and tail spars were installed on the landing and timber nodes, respectively. The physical feasibility of candidate cable corridors between each head and tail spar were evaluated from the DTM, and the feasible corridors were defined as cable nodes. Head spars and tail spars were able to be installed on the landing nodes and timber nodes, respectively.

The site was divided into seven planning areas, delineated by the road network and the outer perimeter of the site (Fig. 4.6c). Table 4.2 summarizes the characteristics of graphs generated in each planning area. The large graph sizes preclude the exact solving of CCL on the graphs. Instead, the value of k in each planning area was varied such that yarded timber nodes comprised 50, 60, 70, 80, 90 or 100% of total timber nodes. Here, this percentage is referred to as the k rate (KR), calculated as

$$KR = \frac{k}{|Z|} \times 100 \tag{4.5}$$

where $|Z|$ is the number of total timber nodes. Therefore, the total number of problem instances to be solved by the algorithms was $7 \times 6 = 42$.

4.4 Experimental results and discussion

Figure 4.8 illustrates the CCLs generated by the two algorithms. The TM algorithm allocated the cable corridors in fan-shaped patterns (Fig. 4.1a), while the Charikar's algorithm added some parallel patterns (Fig. 4.1b). The distinctive patterns generated by each algorithm are attributable to the basic principles of the algorithms.

The TM algorithm successively adds the most profitable timber node and the corresponding path to the solution. In each iteration, if several timber nodes can be yarded without constructing a new landing and/or installing a new cable corridor, one of these nodes will certainly be added to the solution in order to avert the costs of new landing construction and cable installation. In other words, once a landing l_i is constructed, many cable corridors will likely be installed on it. In addition, once a cable corridor c_j is installed, it must first select all timber nodes that can be yarded by c_j and that are not yet included. Therefore, fan-shaped patterns are formed.

The Charikar's algorithm iteratively stores a bunch of the three processes generating the highest average profit. A bunch with high average profit must contain a specified number of timber nodes. Let us recall the definition of density, that is, average profit (Equation 4) and the structure of a bunch in CCL (Fig. 4.5). The presence of multiple timber nodes in a bunch not only increases income but also ameliorates the effects of landing construction and cable installation costs on average profit by increasing the denominator in Equation 4. Because it seeks a certain (preferably large) number of timber nodes in a bunch, the algorithm searches for a cable corridor with low yarding area overlap between the candidate corridor and previously stored cable corridors. This tendency yields parallel patterns with low positional overlap. However, the pattern remains largely non-parallel because the algorithm uses average profit, rather than overlap or geometry, to decide whether a bunch will be stored.

The experimental results are summarized in Fig. 4.9. This figure shows how profitability and computational time vary with KR for the two algorithms. As KR increases, increasing profit indicates that timber income exceeds the cost of cable yarding operations when a new timber node is yarded. Conversely, a decrease in profit denotes an excess of cost over income, and indicates the presence of non-economical timber nodes. As evident from the figure, the profit obtained by the TM algorithm increases with increasing KR, while that obtained by the Charikar's algorithm is convex-upward. To understand these trends, we define the overlap rate (OR), which quantifies the extent of overlapped yarding area among cable corridors, as follows:

$$OR = \frac{OA}{TA} \times 100 \tag{4.6}$$

where OA and TA denote the overlapped and total yarding area, respectively (Fig. 4.10). The OR can be interpreted as the proportion of yarding areas covered by at least two cable corridors, with respect to the total yarding area. A high OR is undesirable because generally overlapping decreases the yarded volume per cable corridor, thereby reducing profit. Figure 4.11 illustrates the effect of KR on OR. The OR of the cable corridors output by the TM algorithm was retained at a high level (between 80% and 95%) for all KR, while that of the Charikar's algorithm rose at least 20% as KR increased from $KR = 50\%$ to $KR = 100\%$. These relationships between KR and OR, arising from the patterns generated by each algorithm, sufficiently explain the trends of Fig. 4.9. In the TM algorithm, the fan-shaped patterns were generated independently of KR, and the OR was more or less constant, leading to the stable profit trend. In the Charikar's algorithm, cable corridors with low overlap became increasingly difficult to construct as KR increased. Therefore, in this algorithm, high KR caused OR to rise and resulted in profit to decline.

The performance of the two algorithms was compared in terms of the relative difference (RD), defined as

$$RD = \frac{P_2 - P_1}{P_2} \times 100 \tag{4.7}$$

where P_1 and P_2 are the respective profits obtained by the TM and Charikar's algorithms. The RD values obtained in our computational experiments are listed in Table 4.3. As indicated in the table, within the KR range from 50% to 90%, the Charikar's algorithm found more profitable layouts than the TM algorithm. The sole exception was planning area No. 6, $KR = 90\%$. On the other hand, at $KR = 100\%$, more profitable layouts were found by the TM algorithm. The average RD was maximized at $KR = 50\%$ (39.6%), and decreased as KR increased. This decrease was approximately linear (16.7%) as KR increased from 50% to 80%, but altered to 13.0% and 37.0% as KR increased from 80% to 90% and from 90% to 100%, respectively. These trends suggest that as the KR is raised, it becomes increasingly difficult to add a profitable cable corridor in the Charikar's algorithm, relative to the TM algorithm. We conclude that given the parameters of our computational experiments, the Charikar's algorithm solves CCL more efficiently than the TM algorithm, except when KR is close to 100%, i.e., when almost all timber nodes are yarded.

In each planning, the Charikar's algorithm yielded the maximum profit for KR ranging from 50% to 80% (Table 4.4). We infer that our formulation, which allows

KR to be less than or equal to 100%, can yield more profitable CCLs than the traditional formulation [37], which restricts KR to 100%. A KR below 100% implies the existence of timber stands that are not harvested in the currently projected cable yarding operations. Such stands should be available for future harvesting, or harvested by ground-based systems if they are adjacent to the road network.

The CPU solution times for problems involving fully harvested timber stands ranged approximately from 2-38 min (Fig. 4.9), which is short enough for practical use. We emphasize that the CPU times required for each planning were recorded at KR = 100%. Both algorithms can be classified as tree construction algorithms that expand a tree from a root. Hence, in solving problems where KR = 100%, they intrinsically generate solutions to problems where KR is less than 100%. Thus, it is not necessary to separately solve both the sets of problems in a specified planning area. All the solutions were improved by the aforementioned improvement procedure of Rayward-Smith and Clare [103] using the Edmonds algorithm. Improvement consumed a maximum of 3 min CPU time.

4.5 Concluding remarks and future work

We presented a new formulation of the CCL problem using graph theory. Our formulation implicitly excludes unprofitable timber stands from yarding operations by introducing a positive integer k as the required number of timber nodes. Furthermore, we showed that this problem is equivalent to k-DST and is solvable using two k-DST approximation algorithms.

The TM algorithm was found to design purely fan-shaped cable corridor patterns, while the Charikar's algorithm adds parallel cable corridor patterns. These characteristic patterns reflect the basic principles of the algorithms. Next, we established that the Charikar's algorithm outperforms the TM algorithm unless the KR is 100%, i.e., unless all timber nodes are yarded. Finally, because it allows the KR to vary, our formulation is superior to the previous formulation [37] with regard to profitable CCL design.

In this study, we adopted existing k-DST approximation algorithms to solve the cable corridor layout problem. However, we recommend that a specialized algorithm be developed for this purpose. The TM and Charikar's algorithms are well suited to solve problems of high and low KR, respectively. Therefore, we propose a simple hybrid algorithm that employs the Charikar's algorithm in the early and middle search stages, and the TM algorithm at the final search stage. Given the highly specialized structure of the input graph, it should be possible to develop a more efficient algorithm with optimal performance and approximation ratio. Moreover, because it determines the location of multiple cable corridors, the problem might benefit from a geometrical approach. For example, the two-dimensional space could be filled with rectangles representing yarding areas of a cable corridor.

In formulating the CCL problem, we omitted several practical considerations. We did not include intermediate supports and made no distinction between uphill and downhill yarding operations. Intermediate supports, which reduce the effect of terrain, should be included in a more efficient CCL design; this issue will be addressed in future work. Particularly for safety reasons, uphill yarding operations are preferable to downhill ones; preferential yarding operations could be modeled using the penalty function of Philippart et al. [98]. Obviously, CCLs designed by an optimization algorithm must be sufficiently verified in the field before application to real-world timber operations, because the solution procedure of the algorithm cannot possibly model the complexity of the real world.

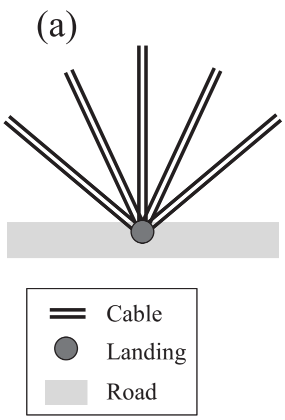

Figure 4.1: Fan-shaped (a) and parallel (b) cable corridor patterns. -

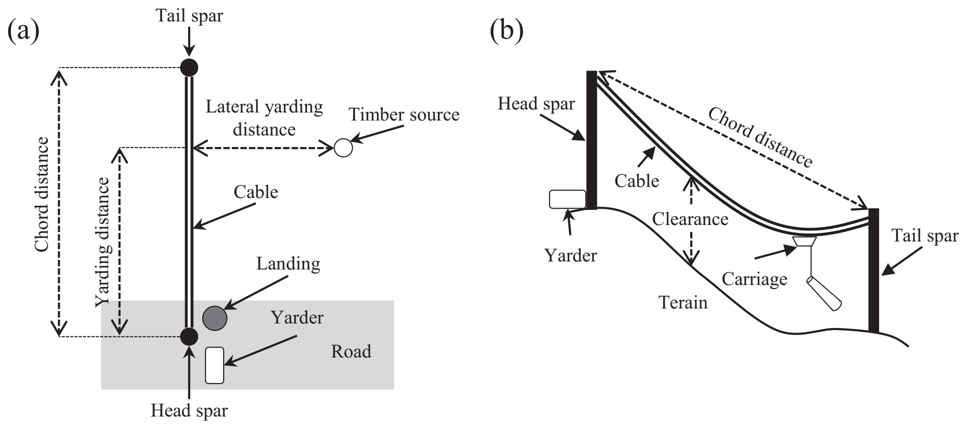

Figure 4.2: Plan view (a) and sectional view (b) of a cable yarding system. -

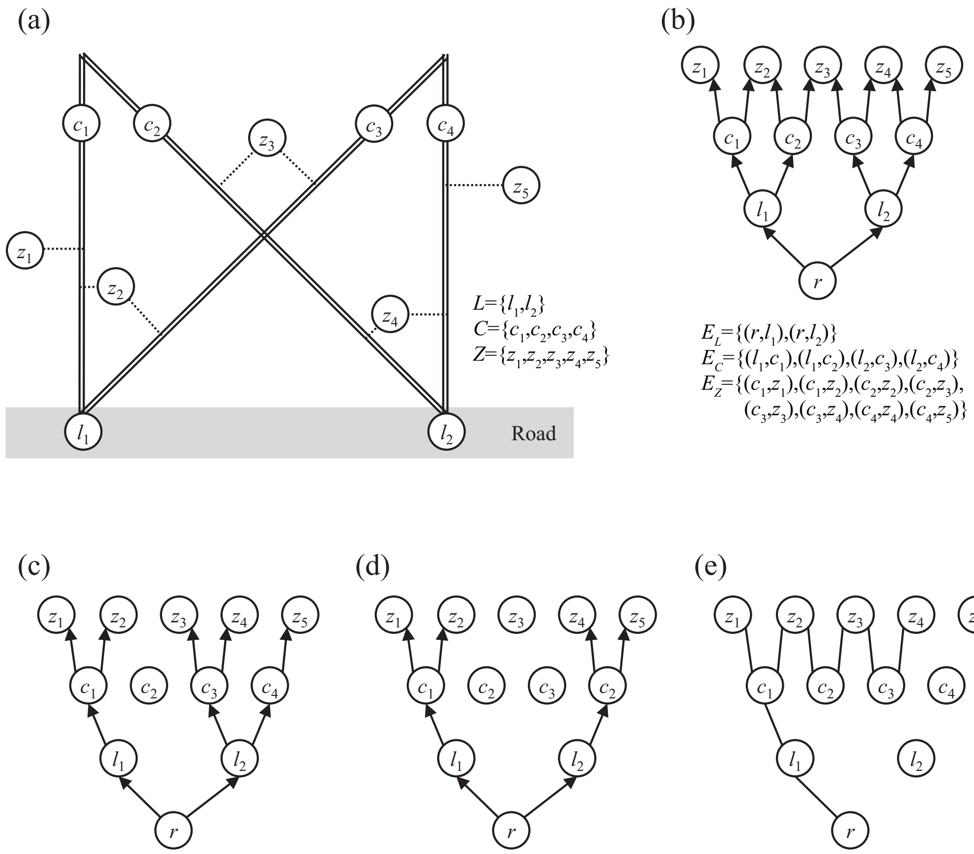

Figure 4.3: Example of CCD - In this example, the planning area contains five timber sources, two candidate landings, and four candidate cable corridors: (a) layout of cable yarding operations; (b) the directed graph; (c) the optimal layout for $k = 5$; (d) the optimal layout for $k = 4$; (e) the optimal layout when the edges are undirected and $k = 4$. The double line indicates a cable corridor; the dotted line denotes a feasible connection between a timber node and a corridor; circles, arrows, and solid lines represent nodes, directed edges, and undirected edges, respectively.

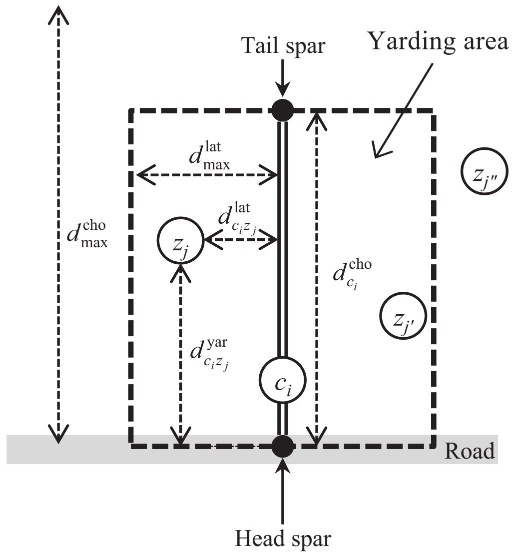

Figure 4.4: Geometric elements in cable yarding operations. - The yarding area of the cable corridor c_i is enclosed within the dashed rectangle. The timber nodes within the area, z_j and $z_{j'}$, can be yarded using c_i, but the node outside the area, $z_{j''}$, cannot be yarded. $d^{\text{cho}}_{\text{max}}$ denotes the maximum chord length (slope distance) of a cable corridor; $d^{\text{lat}}_{\text{max}}$ denotes the maximum lateral yarding distance (horizontal distance).

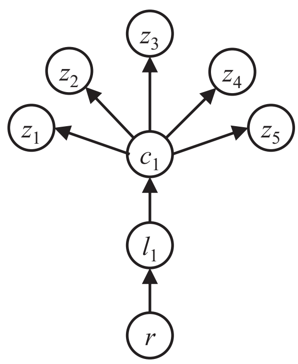

Figure 4.5: Schematic of a bunch in CCD -

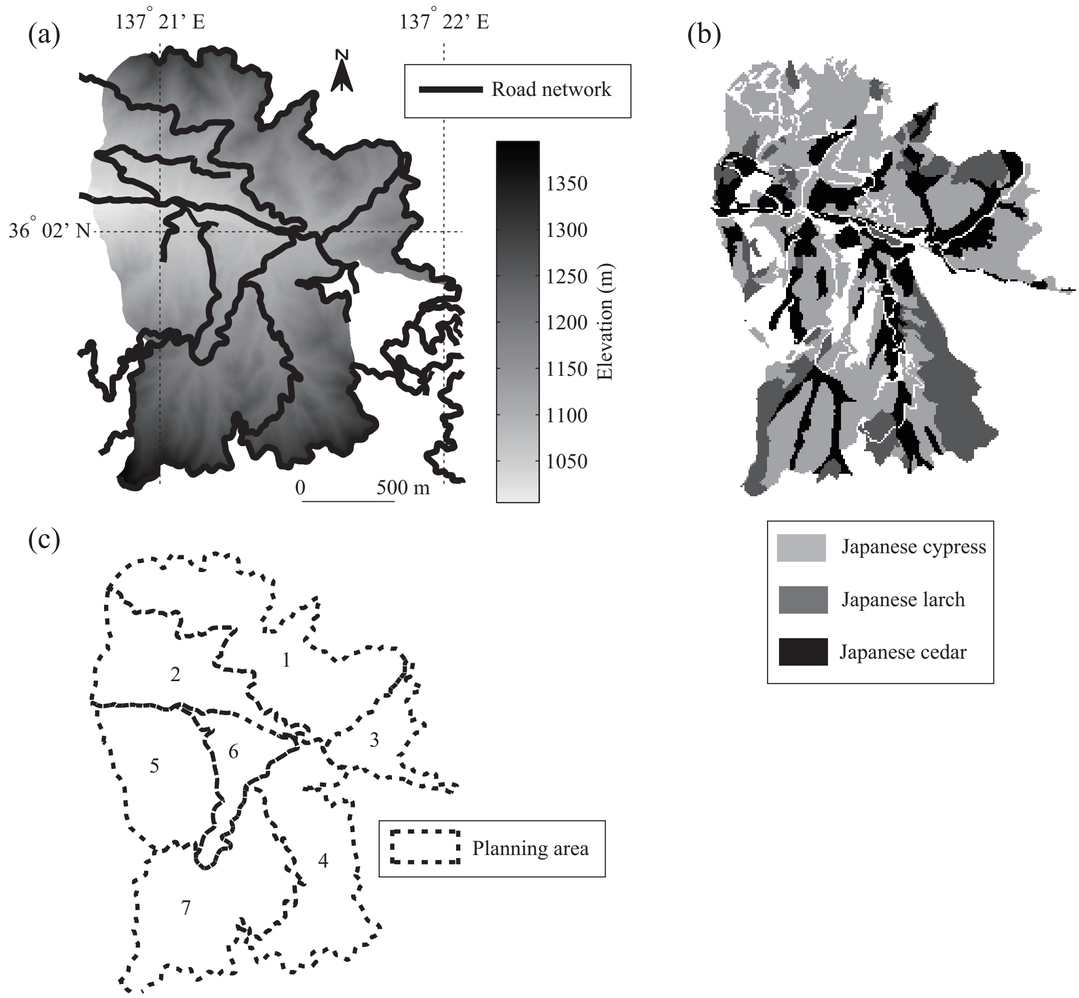

Figure 4.6: Experimental site - (a) Overview; (b) distribution of timber production stands; (c) planning areas.

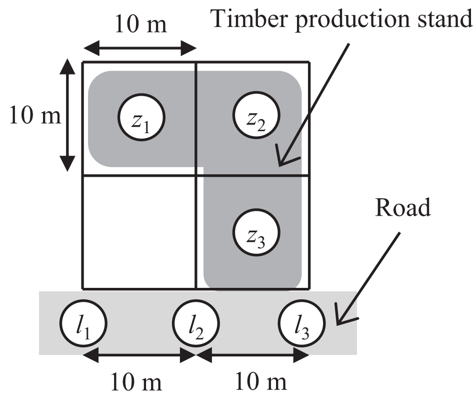

Figure 4.7: Representation of landing nodes and timber nodes -

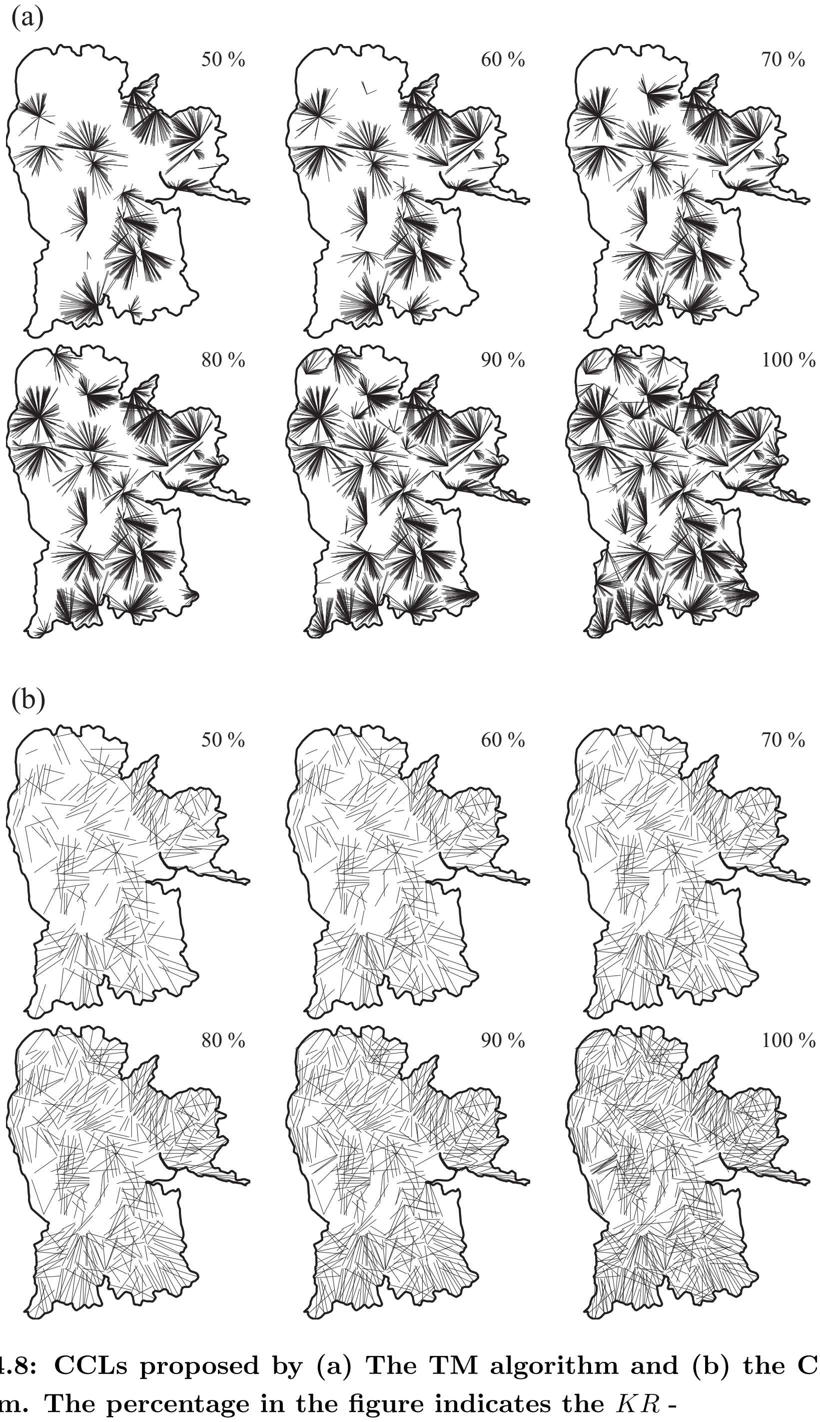

Figure 4.8: CCLs proposed by (a) The TM algorithm and (b) the Charikar's algorithm. The percentage in the figure indicates the KR -

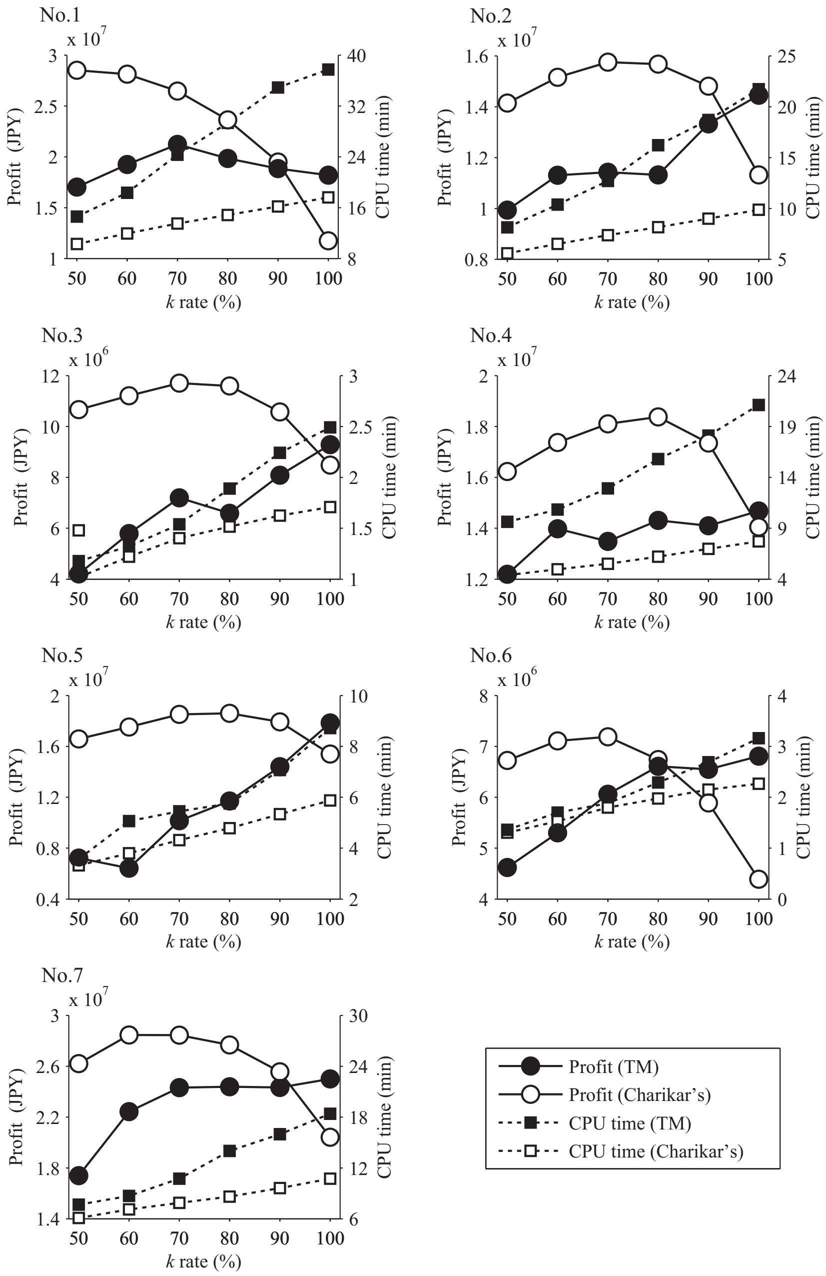

Figure 4.9: Summary of experimental results - Profits and CPU times at each KR are plotted for each planning area (Nos. 1–7). The CPU time represents the time required to solve each problem.

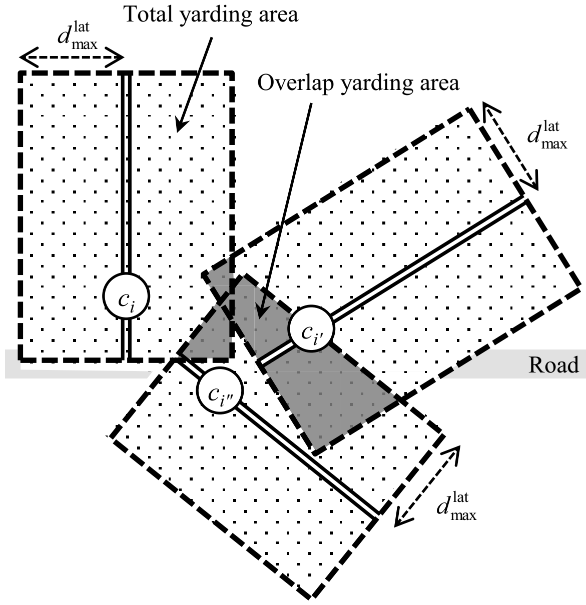

Figure 4.10: Overlapped yarding areas of cable corridors. - The yarding areas of each cable corridor are enclosed in the dashed rectangles. The total yarding area of cable corridors is represented as dots. Overlapping yarding areas are indicated by dense gray areas. $d_{\max}^{\text{lat}}$ is the maximum lateral yarding distance.

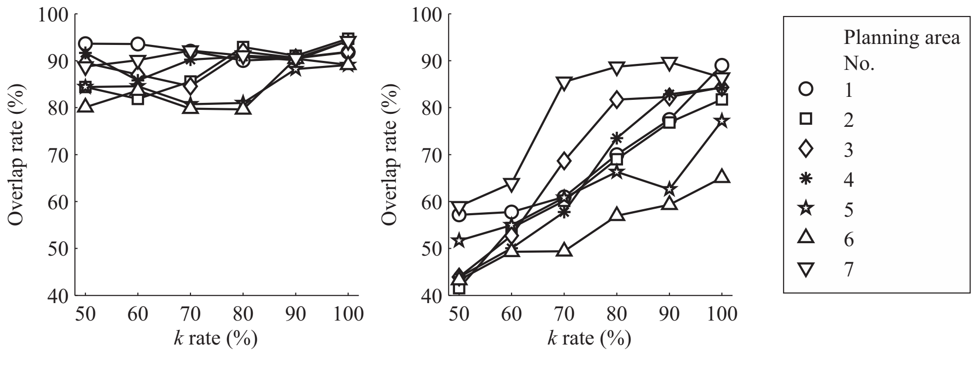

Figure 4.11: Overlap rate - OR (%) as a function of KR. (a) The TM algorithm; (b) the Charikar's algorithm

Table 4.1: Engineering parameters for the cable yarding system used in the computational experiments.

Parameter	Value
Maximum chord length of a cable corridor (m)	300
Minimum chord length of a cable corridor (m)	50
Maximum lateral yarding distance (m)	30
Minimum ground clearance (m)	8
Head spar height (m)	12
Tail spar height (m)	12
Cable horizontal tension (kN)	80
Cable weight (kN/m)	0.015
Number of logs per yarding cycle	1

Table 4.2: Characteristics of the graphs in each planning area. The CPU time is the time required to compute edge weights and construct a graph.

Planning area No.	Area (ha)	Number of nodes			Number of edges			CPU time (min)
		Landing	Cable	Timber	Landing construction	Cable installation	Yarding	
1	63.1	855	300, 673	4, 686	855	300, 673	18, 026, 327	5.5
2	37.0	736	302, 153	2, 419	736	302, 153	17, 260, 620	4.3
3	16.3	581	99, 922	1, 331	581	99, 922	4, 484, 010	1.2
4	46.0	713	236, 557	3, 053	713	236, 557	13, 663, 410	3.9
5	35.9	602	215, 174	1, 898	602	215, 174	11, 702, 035	2.6
6	17.9	632	182, 031	935	632	182, 031	7, 405, 046	2.0
7	52.2	699	202, 388	4, 096	699	202, 388	11, 849, 643	3.5

Table 4.3: Relative difference (percentage) between the profits obtained by the TM algorithm and the Charikar's algorithm.

Planning	KR (%)					
area No.	50	60	70	80	90	100
1	40.3	31.6	19.8	16.0	3.3	−54.9
2	29.8	25.4	27.5	27.8	10.0	−27.7
3	60.5	48.3	38.5	43.1	23.5	−9.5
4	24.9	19.5	25.5	22.1	18.7	−4.5
5	56.5	63.3	45.1	37.0	19.7	−15.9
6	31.3	25.4	15.7	2.0	−11.2	−55.1
7	33.6	21.2	14.5	11.9	4.8	−22.5
Average	39.6	33.5	26.7	22.9	9.8	−27.2

Table 4.4: The maximum profit and KR computed for each planning area.

	TM		Charikar's	
Planning area No.	Profit (JPY, $\times 10^6$)	KR (%)	Profit (JPY, $\times 10^6$)	KR (%)
1	21.2	70	28.5	50
2	14.4	100	15.8	70
3	9.3	100	11.7	70
4	14.7	100	18.4	80
5	17.8	100	18.6	80
6	6.8	100	7.2	70
7	25.0	100	28.5	60

5

Cost-reducing effectiveness of selecting the type of transportation vehicle in a roundwood supply chain

5.1 Introduction

Efforts have recently begun in Japan to carry out the “Forest and Forestry Revitalization Plan”, a large-scale restoration plan for the impoverished forest/ forestry industry [51]. This plan states that optimization of the processing/ distribution system for domestic timber is essential for the promotion of forest resource [52]. Regarding the distribution of raw timber, the placement of satellite yards, the possible location of accumulation sites, and the use of large trailers are being discussed as optimization methods.

When transporting raw timber that is pre-hauled or stacked according to size on the side of roads to timber markets and sawmills, trucks with a maximum payload of 4-7 tons are commonly used in Japan. Small trucks with a maximum payload below 4 tons have come to be used along with the increase of thinned-out wood [140]. In recent years, cost reduction effects brought about by the increase in transportation vehicle size have come to be expected, and empirical examinations are currently being conducted [75, 97].

Past studies regarding transportation costs feature proposals of cost calculation formulas based on transportation vehicle type [107, 112, 128] and provisional calculations for harvesting and transportation that target large forests [110, 157]. However, these calculations assume trucks below 8 tons, and effects on transportation costs created by vehicle selection (especially cost reduction effects obtained by using large transportation vehicles) are not treated quantitatively. Modeling of timber distribution using mathematical programming is also being actively conducted internationally [42]. While there exist examples that regard wide range as well as long-term timber distribution as minimum cost distribution problems with fixed costs [9, 17] and examples that treat short-term timber transportation as truck delivery problems [5, 39, 153], there are no studies that focus on the effects on transportation costs due to differences in transportation vehicles.

The purpose of this study was thus to clarify cost reduction effects obtained by provisionally calculating the transportation costs for using four different types of transportation vehicles of different sizes (2 t truck, 4 t truck, 15 t truck, 24 t trailer).

5.2 Materials and methods

5.2.1 GIS data set

While this study targeted Hyogo prefecture, a GIS data set that covers all of Japan and can be easily obtained was used to enable replication of the analysis without having to restrict regions. Road data were based on the road center line of the numeric map 25000/National Geospatial Framework published by the Geospatial Information Authority [55, Hyogo prefecture version, published in 2003]. The road center line is a vector datum that can be used in network analysis. Table 5.1 shows seven width classifications attached as attributes to road segments. Note that classification 7 (abrupt width change) was absent in the Hyogo prefecture road data. Width classifications used below refer to these categories.

In addition , the Second-5 vegetation survey superposition vegetation vector data provided by the Natural Environment Information GIS of the Center of Biological Diversity of the Ministry of the Environment was used to describe the distribution of forest resources [134]. The data were rasterized into 100 m $\times$ 100 m meshes, then central points were created in the mesh centers. Labels denoting areas of monoculture

(Japanese cedar, Japanese cypress, sawara cypress forestations) were attached to the relevant central points as attributes. In this study, these areas were considered planted forests for the production of timber. Raw timber corresponding to the area was considered to be accumulated in the central points and to be collected as well as yarded on the side of a road (collecting point) nearest to the central point. The maximum distance for yarding was set to 300 m, and raw timber was considered to be extracted only from central points within this distance of the road.

5.2.2 Transportation route

Whether vehicles are able to use a road as well as the transportation velocity depends greatly on road standards [107, 112]. Maximum vehicle width for any road width is determined by the cabinet order on vehicle restrictions. Considering these points, a transportation route as shown in Fig. 5.1 was assumed.

Timber-collecting work is carried out on roads of width classifications 2-6. These roads are passable for 2 t trucks, which are used when transporting raw timber to satellite yards or mills. Their average transportation velocity was determined to be 10 km/h in width classification 2, and 30 km/h in width classifications 3-6. 4 t trucks, carrying out the same tasks, are able to pass through roads of width classifications 3-6. However, raw timber collected at collecting points on roads of width classification 2, where 4 t trucks cannot pass, were transported by forwarders to temporary collecting points on suitable roads, then loaded onto 4 t trucks. The average velocity of 4 t trucks was 30 km/h and that of forwarders, 5 km/h. 15 t trucks and 24 t trailers were able to pass through roads of width classifications 4-6. After raw timber is carried to satellite yards, these trucks were used to transport raw timber on to the mills. Their average transport velocity was considered to be 30 km/h.

When looking at actual raw timber transports, it can be confirmed that vehicles larger than 4 t trucks (such as 8 t and 12 t trucks) are frequently used on 4 t truck routes, as shown in Fig. 5.1. However, this study did not take the use of these vehicles into account, as width classifications attached as attributes where fundamentally only employed to determine whether vehicles were able to pass through on the road. Deciding whether 8 t or 12 t trucks would be able to use the road on the strength of the width classifications only was also considered unreliable. Determining this for roads of width classification 3 would require road data with attributes such as more detailed width classification and the radius of curves. Realistically, the selection of transport vehicles shown in Fig. 5.1 would be insufficient for clarifying the most suitable transport vehicle, but as the purpose of this study was to clarify the effects of selecting transportation vehicles based on costs, only vehicles that were clearly determined to be able to pass any given road were used.

5.2.3 Outline of the study area

Hyogo prefecture, the study' target region, features several regional characteristics. A large sawmill with an annual consumption target of raw timber of over 120,000 m^3 and the Cooperative Association Hyogo Timber Center (hereafter referred to as the timber center) operate in Shiso City , located in the central western area of the prefecture [71, 135]. There are no sawmills for the consumption of B timber within the prefecture. There are seven satellite yards referred to as stock points, established to deal with trees that were brought down by the typhoon in 2004 [137]. The timber center is a sawmill mainly for sawing A timber. However, tree-selecting devices have been implemented, so that B timber is mainly sent to the veneer mill in Maizuru City in Kyoto prefecture. This selection capacity enables a system where all raw timber can be collated at the timber center without previous sorting at places where timber is gathered. As the competence for operating satellite yards is present in Hyogo prefecture, most stock point locations can also be easily arranged for use as satellite yards.

A trial calculation of costs was conducted by allowing for the circumstances mentioned above, assuming the mill in Fig. 5.1 to be the timber center, and assuming a total of eight satellite yards (there are seven locations that functioned as stock points in the past and one more satellite yard currently operating). The total area included in the model was 84,112.1 ha. The Akashi Kaikyo Ohashi Bridge, which has a high toll, must be used to access the forest of Awajishima, or alternatively raw timber must be transported to Honshu using a shipping company. This forest was therefore removed as a target from the trial calculation. The position of these facilities and the distribution status of forests supplying raw timber in this study is shown in 5.2. (black sections correspond to forests). The distribution of transportation distances in the case of transporting raw timber to the timber center using the shortest distance is shown in Fig. 5.3. 50.7 % of the forests have a transportation distance of over 50 km, and 8.5 % have over 100 km.

5.2.4 Transportation cost trial calculation pattern

The trial calculation of transportation costs was conducted based on the following four patters (A-D). In the case of transportation routes using multiple vehicles, the transportation cost was the total of all vehicle costs, and it was assumed that there was no waiting time arising from differences in the amount of work involved. Pattern A: only 2 t trucks. Pattern B: only 4 t trucks. Pattern C: either 2 t trucks or 4 t trucks. Pattern D: pattern C, plus 15 t trucks or 24 t trailers when going through satellite yards. When using 4 t trucks, forwarders were also employed if necessary. Transportation using roads of width classification 2 was kept to a minimum to help reduce transportation costs; this means that the shortest distance was not always selected. While there were several transportation routes in patterns C and D, those with the lowest cost were assumed to be selected.

5.2.5 Transportation cost calculation formula

Transportation cost in this study refers to the cost of transporting timber collected on the side of roads to the timber center. In the cost trial calculation, the formation or position of the places of operation were not specifically set, and the potential transportation costs of each forest were calculated.

Parameters used in calculation are shown in Table 5.2. The machine price of 24 t trailers and the number of operating days of trucks were based on hearing investigations towards timber transportation industries operating large trailers in Hyogo prefecture. As t he load productivity of large vehicles (15 t truck / 24 t trailer) was expected to differ from the productivity of small vehicles (2 t / 4 t truck), a measurement of load productivity for 15 t trucks using grapple loaders (12 t class base machine) was conducted and values were set based on the survey result.

Most existing studies [107, 110, 112, 128, 157] search for transportation costs using continuous linear functions where the explanatory variable is the transportation distance. However, an increase in the number of transportations per day does have an effect on transportation costs [46]. Thus, a calculation formula including the number of transportations was used in this study.

First, based on the assumption that there is at least one transportation per day and that the transportation vehicle will always return to its point of departure within that day, the number of transportations y per day was determined using the following equation.

$$y = \max\left(\left\lfloor \frac{N}{2 \times x/\sigma + T_{lu}} \right\rfloor, 1\right) \tag{5.1}$$

where max is the function that returns the maximum value, $\lfloor\rfloor$ is the function that shows the upward or downward rounding of integers, N is operating time per day (time/day), x is transportation distance (km) and T_{lu} is the amount of time for loading / unloading once (time/number of times). T_{lu} is referred to as the terminal time, and develops with no direct relation to transportation distances. Figure 5.4 shows the relation of transportation distance by vehicle type to number of transportations per day, assuming a transportation velocity of 30 km/h. In the case of 2 t and 4 t trucks, multiple transportations per day are possible until total transportation distance exceeds 50 km. On the other hand, 15 t trucks are limited to distances of less than 40 km and 24 t trailers to less than 20 km, which makes multiple transportations impossible. This is due to length of terminal time.

Next, transportation cost z per unit timber volume was determined by the following equation. Costs related to tree cutting / collecting work were not included in the transportation cost.

$$z = \frac{F + 2 \times V \times x \times y + E + C \times y}{Q \times y} \tag{5.2}$$

where F is the fixed cost of transportation vehicles per day (JPY/day), V is the variable cost of transportation vehicles per unit distance (JPY/km), E is the labor cost of transportation vehicle drivers per day (JPY/day), $C$is the expense for loading / unloading per day (JPY/day), and Q is the transported amount for one ransportation (m^3/number of times). C describes the cost for loading and unloading machines and workers, and is shown in Table 5.3. Attached grapples were used for work with forwarders, and grapple loaders were used for other vehicles.

The relation of transportation cost to transportation distance by vehicle is shown in Fig. 5.5. Since the relationship of transportation amount per day to transportation distance varies discontinuously based on the number of transportations, the transportation costs also have discontinuous values. Vehicles with the lowest cost for each transportation distance are shown in Fig. 5.5. The vehicle with the lowest cost against the transportation distance is shown in Fig. 5.6. Up to 0.3 km these are 2 t trucks; for

0.3-8.9 km, 4 t trucks; for 8.9-13.9 km and 18.3-33.9 km, 15 t trucks; and 24 t trailers for distances of 13.9-18.3 km and more than 33.9 km.

5.3 Results and discussion

5.3.1 Trial calculation results

Average values, medians and quartiles of transportation costs obtained as a result of all four patterns of trial calculations are displayed in Table 5.4 together with the corresponding transportation routes, average transportation distances, route selection frequencies, and ratios of selection based on forest area.

5.3.2 Patterns A and B

Figure 5.7 shows the distribution of transportation costs when using only 2 t trucks (Pattern A), and when using 4 t trucks together with occasional and facultative use of forwarders (Pattern B). Histogram colors are based on the number of transportations per day. The average transportation cost was 6,015.5 JPY/m^3 for 2 t trucks and 4,952.1 JPY/m^3 for 4 t trucks (Table 5.4). In the case of both patterns having few transportations, the transportation amount per day became low due to small vehicle size, and transportation cost increased. The number of transportation per day became 1 when the transportation distance exceeded 50 km (Fig. 5.4). However in this case, the transportation cost exceeded 9,000 JPY/m^3 in Pattern A and 5,000 JPY/m^3 in Pattern B (Fig. 5.7). In Pattern B, transportation costs were not completely determined by the number of transportations by 4 t truck. This is due to the fact that transportation costs are high even when there are many transportations, and also because of reloading by forwarder transportation in some forests.

5.3.3 Pattern C

The distribution of transportation costs when 2 t and 4 t trucks are selectable (Pattern C) are shown in Fig. 5.8, and the distribution map of selected routes is shown in Fig. 5.9. If no forwarder transportation is assumed, 4 trucks are selected if the transportation distance does not exceed 0.3 km (Fig. 5.6). However, when assuming costly forwarder transportation and in forests requiring this, 4 t trucks tended to be avoided. The average transportation distances of 2 t and 4 t trucks were 29.4 km and 53.8 km (Table 5.4). It can also be seen that 2 t trucks were selected around the timber center (Fig. 5.9).

The average transportation cost of Pattern C was 4,399.1 JPY/m^3. This corresponds to a reduction of 1,616.4 JPY/m^3 compared to Pattern A and a reduction of 553.0 JPY/m^3 compared to Patter B (Table 5.4). Causes of cost reduction include the fact that 4 t truck transportation, which has lower costs, was selected for forests distant from the timber center where the use of 2 t trucks would result in higher costs. Also note that 2 t truck transportation with lower cost was selected in preference of 4 t trucks in forests requiring long distance forwarder transportations. Thus there existed a mutual and complementary relationship between 2 t and 4 t trucks, making it possible to reduce transportation costs by using both types of vehicles.

5.3.4 Pattern D

The distribution of transportation costs when using large vehicles (15 t trucks / 24 t trailers) in addition to 2 t and 4 t trucks (Pattern D) is shown in Fig. 5.10, and the distribution map of selected routes in Fig. 5.11. By comparing Fig. 5.8 and Fig. 5.10, it can be seen that large vehicles were selected in Pattern D for forests located far from the timber center where only transportation per day was carried out, even by using the smaller trucks.

ransportation with large vehicles was selected in 51.6 % of forests, and the average transportation cost was 3,586.2 JPY/m^3 (Table 5.4). This corresponds to a reduction of 812.9 JPY/m^3 compared to Pattern C. In contrast , there was an increase in average transportation distance of 18.2 km in Pattern D compared to other patterns, owing to transportations through satellite yards.

Regarding transportation vehicles beyond the satellite yard stage, 15 t trucks were selected at the satellite yard closest to (south of) the timber center since this type of truck was able to transport twice a day here, which was not possible with 24 t trailers. In all other satellite yards, 24 t trailers with their advantage in long distance transportation were selected, twice-daily transportation with 15 t trucks not being possible. In the simulation, the number of transportations for large vehicles was restricted to once or twice per day due to long loading / unloading (terminal) times (1.7 hours for 15 t trucks, 2.8 hours for 24 t trailers) (Table 5.2). The increase of number of transportations per day through reduction of terminal time is clearly an important factor for further cost reduction in transportation using large vehicles.

In Pattern D, transportation routes using large vehicles were selected for forests in distant locations from the timber center due to lower transportation costs over long distances. It may be suggested that large vehicle transportation through satellite yards is a promising means of low cost transportation in raw timber distribution centering on the Hyogo prefecture timber center. The trial calculation does however assume a simple transportation route, as shown in Fig. 5.1. Since initial investment costs and management / operation expenses of satellite yards were not taken into account, further detailed investigations are necessary regarding the use of satellite yards.

5.4 Conclusions

Transportation cost reduction is an essential part of general cost reduction in the timber production industry. In this study focused on Hyogo prefecture, trial calculations of transportation costs were conducted by assuming transportation routes using vehicles of different sizes. It was confirmed that being able to select multiple different transportation vehicles can result in cost reduction effects if there exists a mutual and complimentary relationship between vehicles. Cost reduction effects resulting from employing larger transportation vehicles were clarified through the simulation by using large vehicles for transportation from satellite yards. It was shown that an appropriate selection of transportation vehicles is effective in reducing transportation costs when the layout of forests and destinations, transit points and locations and road statuses is taken into sufficient account.

It is suggested that future research might increase the number of types of transportation vehicles as well as distribution facilities, assume a more realistic raw timber distribution, and clarify the most suitable transportation vehicles as well as transportation routes. It should also be noted that return cargo transportation was not included in these trial calculations. Return cargoes in particular have effects on transportation costs when dealing with large vehicles or long distances. A further promising research area would be cost calculation methods that consider return cargo transportations.

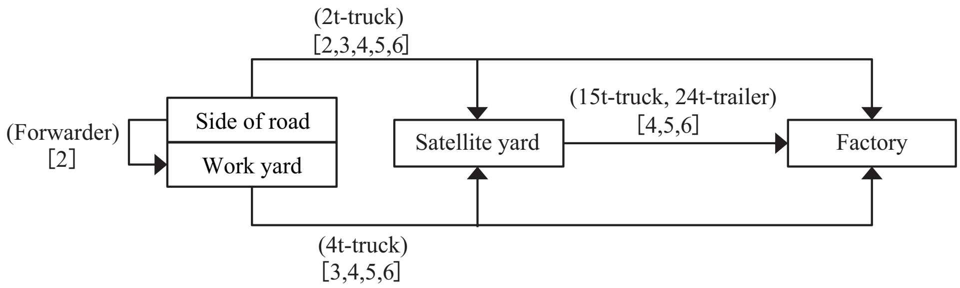

Figure 5.1: Transportation route - Terms in parentheses indicate transportation vehicles. Values in square brackets indicate road width classifications.

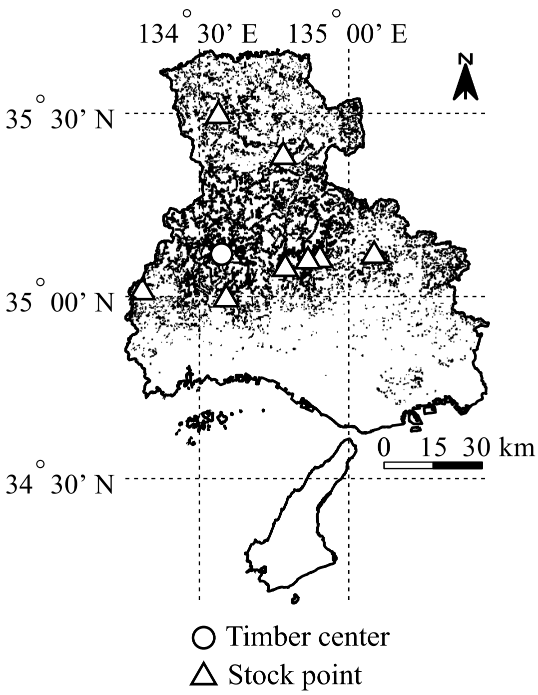

Figure 5.2: Overview of the study area -

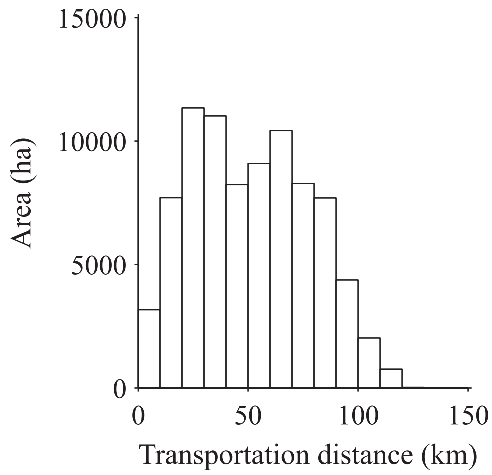

Figure 5.3: Distribution of shortest transportation distances -

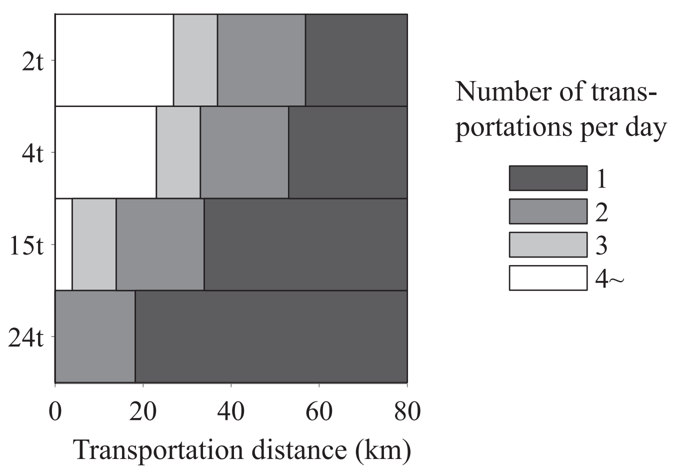

Figure 5.4: Relationship between transportation distance and number of transportations -

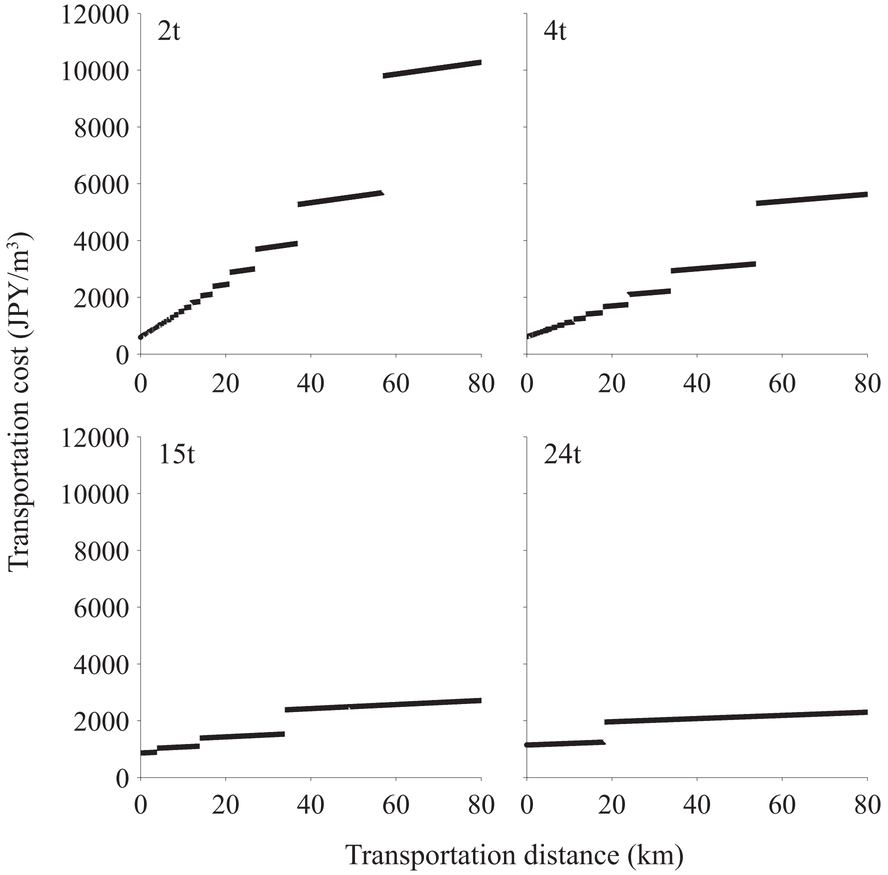

Figure 5.5: Relationship between transportation distance and transportation cost -

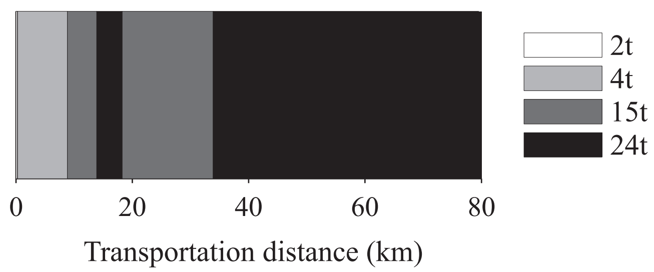

Figure 5.6: Transportation vehicles with the lowest transportation cost for a given transportation distance -

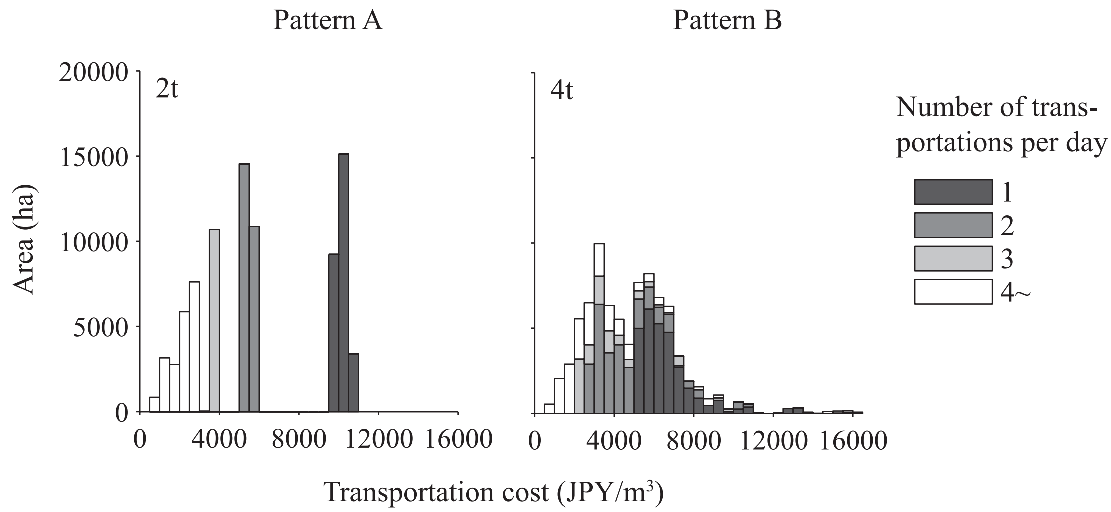

Figure 5.7: Distribution of transportation costs (Pattern A, Pattern B) -

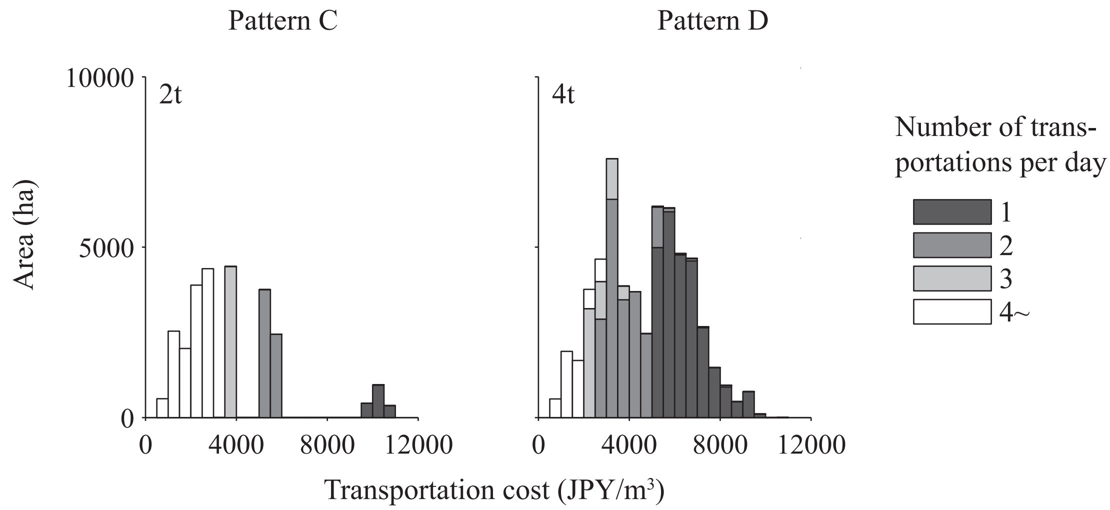

Figure 5.8: Distribution of transportation costs (Pattern C) -

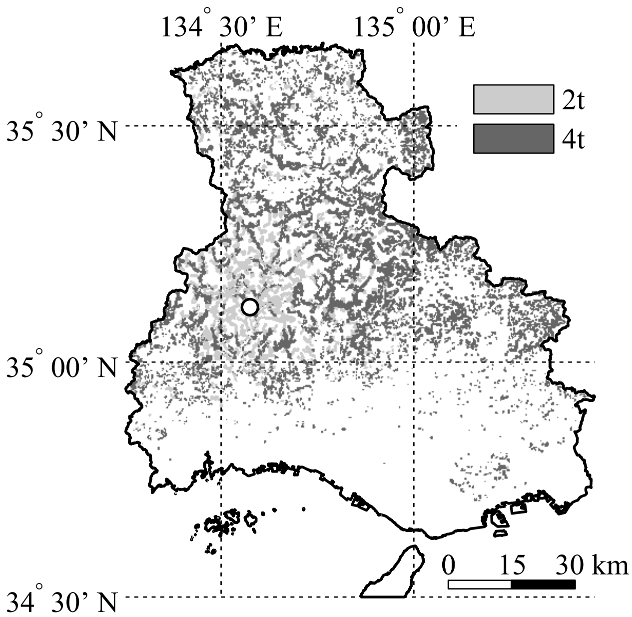

Figure 5.9: Distribution map of transportation routes (Pattern C) -

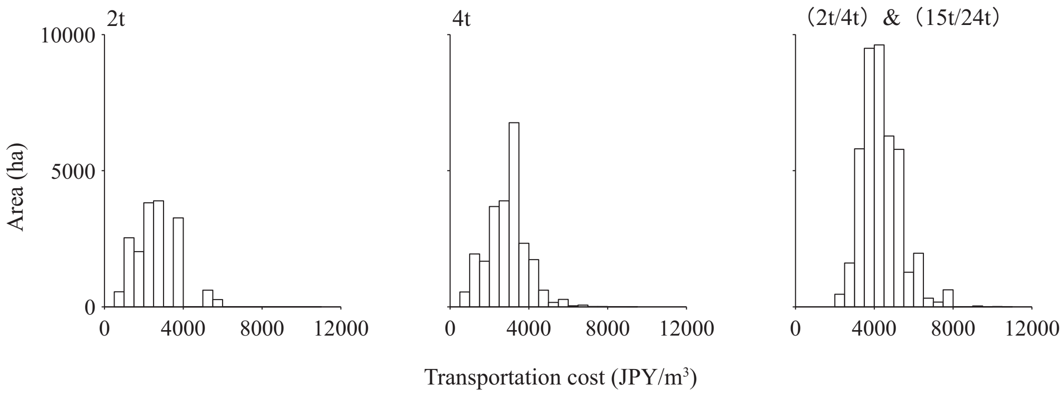

Figure 5.10: Distribution of transportation costs (Pattern D) -

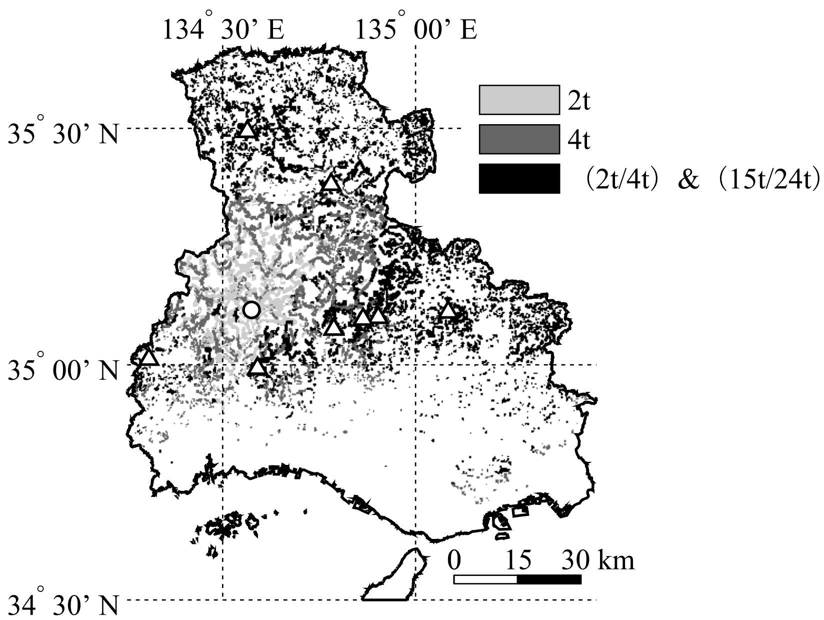

Figure 5.11: Distribution map of transportation routes (Pattern D) -

Table 5.1: Road width classification in the road data.

Attribute name	Classification	Content
Road width	1	Less than 1.5 m
	2	Between 1.5 m and 3 m
	3	Between 3 m and 5.5 m
	4	Between 5.5 m and 13 m
	5	Between 13 m and 25 m
	6	Over 25 m
	7	abrupt change section

Table 5.2: Parameters for calculating transportation costs.

Parameter	Units	Symbol	Forwarder	2t truck	4t truck	15t truck	24t trailer	Formula or reference
Maximum load weight	t	W	2.8	2	4	15	24	Forwarder: Q/q
Maximum load quantity	m^3	Q	3.5	2.5	5.0	18.8	30.0	Forwarder: [74] Except forwarder: $W \times q$
Initial purchase price	JPY × 10,000	P	1,200	350	407	1,210	2,000	Forwarder: [74] 2t truck: Selling price 4t truck and 15t truck: [72] 24t trailer: Hearing investigation
Horsepower	kw	H	149.6	110	137	272	338	Forwarder: [74] Except forwarder: [90]
Specific fuel consumption	l/kw · hour	SFC	0.16	0.05	0.05	0.05	0.05	[44]
Mean travel speed	km/hour	σ	5	30 (10)	30	30	30	
Fuel efficiency	km/l	e	0.21	5.5	4.4	4.1	1.8	$\sigma/(SFC \times H)$
Number of durable years	year	L	6	5	5	5	5	Statutory durable years
Number of operating days per year	day	M	130	250	250	250	250	Forwarder: [74] Except forwarder: Hearing investigation
Number of operating hours per day	hour	N	6	8	8	8	8	Forwarder: [74] Except forwarder: Hearing investigation
Capital recovery factor		CRF	0.18	0.21	0.21	0.21	0.21	$i \times (1+i)L/((1+i)L-1)$
Annual interest rate		i	0.02					
Rate of annual storage and license cost		μ	0.048	0.12	0.12	0.12	0.12	Forwarder: [74] Except forwarder: [72]
Rate of maintenance and repair cost		ν	0.38	0.55	0.45	0.45	0.35	Forwarder: [74] Except forwarder: [72]
Loading volume per cycle	m^3/cycle	α_l	0.25	0.20	0.20			[74]
Unloading volume per cycle	m^3/cycle	α_u	0.30	0.40	0.40	0.40	0.40	[74]
Loading cycle time	second/cycle	β_l	50	44	44			[74]
Unloading cycle time	second/cycle	β_u	25	25	25	25	25	[74]
Loading productivity	m^3/hour	ρ_l	18.0	16.4	16.4	13.9	13.9	Except 15t–truck and 24t–trailer: $\alpha_l/\beta_l \times 3600$ 15t truck and 24t trailer: Productivity measurement
Unloading productivity	m^3/hour	ρ_u	43.2	48.0	48.0	48.0	48.0	$\alpha_u/\beta_u \times 3600$
Loading and unloading time per operation	hour	T_{lu}	0.28	0.20	0.41	1.7	2.8	$Q \times (1/\rho_l + 1/\rho_u)$
Truckload quantity of timber	m^3/t	q	1.25					[44]
Unit fuel price	JPY/l	k	107.5	107.5	107.5	107.5	107.5	[27]
Fixed cost	JPY/day	F	2,0910.1	4,650.2	5,407.5	16,076.5	26572.7	$D + S + I$
Depreciation cost	JPY/day	D	15,384.6	2,800.0	3,256.0	9,680.0	16,000.0	$P/(L \times M)$
Storage and license cost	JPY/day	S	4,430.8	1,680.0	1,953.6	5,808.0	9,600.0	$\mu \times P/M$
Capital interest	JPY/day	I	1,094.7	170.2	197.9	588.5	972.7	$(CRF \times P \times L - P)/(L \times M)$
Variable cost	JPY/km	V	702.9	26.1	30.7	66.9	83.9	$R + O$
Maintenance and repair cost	JPY/km	R	194.9	6.4	6.1	18.2	23.3	$I \times \nu/(\sigma \times L \times M \times N)$
Fuel cost	JPY/km	O	508.0	19.7	24.5	48.7	60.6	k/e
Labor cost	JPY/day	E	15,900					[72]

Table 5.3: Loading and unloading cost.

Parameter	Units	Symbol	Forwarder	2t truck	4t truck	15t truck	24t trailer	Formula or reference
Loading and unloading cost per operation	JPY	C	270.1	960.3	1,920.6	8,154.3	13,046.9	$T_{lu} \times (F_{lu} + V_{lu} + E_{lu})$
Fixed cost	JPY/hour	F_{lu}	0	1,719.5				[74]
Variable cost	JPY/hour	V_{lu}	980.6					[74]
Labor cost	JPY/hour	E_{lu}	0	1,987.5				[72]

Table 5.4: Calculation results.

Pattern	Transportation vehicle	Transportation cost (JPY/m^3) Average	First quartile	Median	Third quartile	Average transportation distance (km)	Selected percentage (%)
A	2t truck	6,015.5	3,682.6	5,439.7	9,933.3	46.3	100.0
B	4t truck	4,952.1	3,082.9	4,767.0	6,275.5	46.3	100.0
	2t truck/4t truck	4,399.1	2,932.4	4,033.9	5,652.3	46.3	100.0
C	2t truck	3,767.1	2,084.7	2,968.0	5,315.4	29.4	30.6
	4t truck	4,677.7	3,054.9	4,766.3	6,192.3	53.8	69.4
	2t truck/4t truck & (15t truck/24t trailer)	3,586.2	2,904.8	3624.1	4,394.1	64.5	100.0
	2t truck	2,610.7	1,792.9	2,430.3	2,982.3	19.5	20.2
D	4t truck	2,884.4	2,156.9	3,003.5	3,170.9	35.7	28.2
	2t truck /15t truck/24t trailer	4,321.2	3,652.8	4,181.9	4,770.9	90.0	32.6
	4t truck & (15t truck/24t trailer)	4,402.1	3,634.1	4,282.3	5,079.4	111.4	19.0

6

Reducing distribution costs by using satellite yards in a roundwood supply chain

6.1 Introduction

Scale expansion of the involvement of plywood factories and sawmills in log distribution in Japan has seen some advancement in recent years , as exemplified by the "New Wood Production Projects" conducted by the Forestry Agency to promote utilization of domestic timber [61]. The construction of a stable log supply system that can meet the demands of large factories is at present the biggest challenge [62]. To this end, further optimization of log supply systems beginning with the reduction of material production costs and distribution costs is necessary.

As stated in Japan' Basic Plan for Forest and Forestry revised in 2011, the use of satellite yards is recognized as one measure for optimization [50], and its empirical investigation is being advanced nationwide [75, 97]. Satellite yards are yards placed at midway points between forests where logs are supplied and supply destinations such as log markets and mills. They are large–scale compared to work yards and locations for gathering timber adjacent to cutting sites, and have a larger collecting range. Practical effects of placing satellite yards include the use of large transportation vehicles when transporting from satellite yards to supply destinations and the securing of service stock that can respond to short-term requirements of factories. The availability of sorting capabilities also enables procedures such as shipping high quality logs that can expect high prices to log markets, while shipping low quality logs to factories. Improvements in profitability can thus be expected.

The purpose of this study was to quantitatively evaluate the effectiveness of satellite yards for the reduction of distribution costs while testing various yard placement configurations.

The mathematical programming model was used for developing the placement proposal. In such an approach, the effects of placing and establishing facilities as well as operation costs must be evaluated to determine whether the effects are worth the invested costs. To maximize cost effectiveness, it is also necessary to decide how many facilities should be placed in a given location, and some decisions require combination factors. The use of mathematical programming models is effective in supporting such decision making processes. Sessions and Paredes [116] developed a mathematical programming model of log yard placement, and Sessions et al. [118] improved the model by taking into account uncertainties involved in the sorting work at log yards. Chan et al. [18] proposed a model that decides the positioning of machines for delimbing, bark peeling, and chipping in addition to the placing of satellite yards. Other logistics studies treating log distribution using mathematical programming models are being actively developed internationally [12, 32, 42, 106, 148]. Very few studies however have focused on transportation cost reduction effects by using large vehicles for transportation from satellite yards. This reduction effect is likely a particular feature of localities where it is difficult to construct road systems wide enough for large vehicles and where only small vehicles can be used between log collecting grounds and yards – in other words, as in some Japanese regions where forests exist on steep and complex landforms.

6.2 Materials and methods

6.2.1 Model outline

This study generated a layout plan of satellite yards for a scenario involving the Cooperative Association Hyogo Timber Center (hereafter referred to as the timber center), located in Shiso City, Hyogo prefecture, supplying logs to their factory. The timber center has been operating since December 2010. It comprises a large sawmill that handles an annual volume of 126,000 m^3 of logs and a production volume of 63,000 m^3

both figures are target amounts) [135]. The modeled time period was 5 years, and it was assumed that 5 years worth of logs (630,000 m^3) to be used in the timber center would be supplied. The model' purpose was to determine the most suitable location for satellite yards to minimize the distribution cost F of supplying logs. F here refers to the total transportation costs incurred when collecting logs on forest routes for deposition on roadsides as well as transporting these logs to the timber center. It also includes fixed costs for the establishment as well as operation of satellite yards. The timber center contains an automatic log-selecting machine, hence it was assumed that unsorted logs would be supplied to the center. To simplify log supply activities, the collecting range was limited to all areas of the Hyogo prefecture excluding Awajishima. It was also assumed that logs would not be supplied by log distributors such as log markets, as there is a stable log supply system based on log distribution agreements with forest owners as well as on system distribution contracts with national [133], and hence logs can be supplied without having to rely on log distributors.

6.2.2 Reduction effect of distribution costs

As mentioned above, the layout effects of satellite yards include the improvement of profits as a result of inventory adjustment and sorting in addition to the reduction of distribution costs through the use of large transportation vehicles. However, this study only evaluated the latter effect. The reduction effect of distribution costs E is shown as the difference between the distribution cost F' of the model that does not assume placement of satellite yards, and distribution cost F of the proposal that does.

$$E = F' - F \tag{6.1}$$

6.2.3 Mathematical programming model

Following previous studies [18, 116], the mathematical programming model for the most suitable location of satellite yards is formulated as a fixed-charge transportation problem in a network G that consists of a set L of forests supplying logs, a set M of candidate locations for satellite yards, and a set N of factories [67]. The objective function is the distribution cost F, and is expressed in minimized form through the following formula.

$$\text{minimize} F = \sum_{i \in V} \sum_{j \in V} c_{ij} \cdot x_{ij} + \sum_{m \in M} d_m \cdot y_m \tag{6.2}$$

where V is the node set of network G, c_{ij}, x_{ij} are the transport unit costs (JPY/m^3) from node $i \in V$ to $j \in V$, and the transportation amount (m^3). y_m is the binary determining placement of a satellite yard at $m \in M$, and d_m is the fixed cost (JPY) over 5 years (model period) in the event of placing a satellite yard in candidate location m. Term 1 shows total transportation cost of logs and term 2 shows total fixed satellite yard cost. The constraint equation is shown below.

$$\text{subject to} \quad \sum_{l \in L} x_{lm} = \sum_{n \in N} x_{mn} \qquad \forall m \in M \tag{6.3}$$

$$\sum_{j \in V} x_{lj} = q_l \qquad \forall l \in L \tag{6.4}$$

$$\sum_{l \in L} x_{lm} \leq (\sum_{l \in L} q_l) \cdot y_m \qquad \forall m \in M \tag{6.5}$$

$$x_{ij} \geq 0 \qquad \forall i, j \in V \tag{6.6}$$

$$y_m \in \{0, 1\} \qquad \forall m \in M \tag{6.7}$$

where q_l is the log volume (m^3) of logs produced by forest section $l \in L$. Equation 6.3 shows the flow conservation laws for m: the amount of logs that will be transported to satellite yard m and the amount of logs that will be transported from m is the same. Equation 6.4 shows that all logs produced in forest section l will be transported. Equation 6.5 is a constraint equation that prevents the passing of logs through unopened satellite yards. Equation 6.6 is a non-negative constraint equation that shows that the transportation amount x_{ij} is not negative, and Equation 6.7 is a binary constraint of the binary variable y_m.

6.2.4 Node set

The set N of factories in this study is a singleton that is constructed from the timber center 1 node. The set M of candidate locations of satellite yards was chosen to assure equal distribution across all areas of the collecting range, and was created using the following steps. First a 10 km $\times$ 10 km square mesh was overlaid on the area. Next, location nodes were constructed on roads passable by 24 t trailers with the shortest distance from the center of each mesh. These nodes made up set M of the candidate locations of satellite yards. Roads open to 24 t trailers correspond to those with a width of more than 5.5 m, following a previous study [122]. Seventy-eight candidate locations were set. The timber center and position of candidate locations are shown in 6.1.

The Japanese cedar / cypress-planted forest polygon included in the Second-5 vegetation survey of the natural environment information GIS (Center for Biological Diversity of the Ministry of the Environment) was used as basis for the set of forests producing logs L [134]. The set was created using the following steps. First the planted forest polygon was divided into 100 m $\times$ 100 m square meshes, then forest section nodes were constructed in the center of meshes. Next, the amount of logs produced in each forest section node was calculated by multiplying the area of the planted forest polygon included in each mesh with yield of logs per unit area α. This study assumed thinning works to be carried out, therefore α was uniformly set as 50 m^3/ha. Finally, forest section nodes were randomly added to L until values reached the target amount of logs to be supplied. Only nodes within 300 m of the road were added in this manner, as the 5 year model period in this study is relatively short and generally there is a higher possibility that forest works will be carried out in forest sections closer to roads [120]. There were 110,526 forest section nodes within 300 m of roads (Fig.6.2). 100 L were created and a model was created for each L. The average number of elements per set was 19,435.3.

6.2.5 Transportation unit cost and fixed cost

The transportation vehicles used in the model were forwarders, 2 t trucks, 4 t trucks, 15 t trucks, and 24 t trailers. Forwarders, 2 t and 4 t trucks were assumed to be used in transport from forests to the timber center as well as from forests to satellite yards. 15 t trucks and 24 t trailers were assumed to be used between satellite yards and timber center. The previous study [122] included a trial calculation of the transportation price unit of these five types of transportation vehicles. In the present study the transportation unit price was set using the same method. Costs incurred by the loading / unloading work that accompanies transportation were also added to this transportation unit price. The road data used for the calculation of transportation distance was the road center line of the numeric map 25000/ National Geospatial Framework [55], and width classifications were attached to the road data. The calculation method of transportation unit cost, calculation parameters, and the road width method for determining whether vehicles could pass followed the previous study.

As shown in Equation 6.2, fixed costs in transportation problems are not related to transportation amounts and emerge when establishing or using facilities that relate to transportation work. The fixed cost of satellite yards can be thought of as composed of the purchase cost of land or land rent, and labor costs of manager and operators. However, as it was difficult to accurately estimate the fixed cost of the 5 year model period for each of the 78 candidate locations, it was decided to assign a uniform fixed cost d (JPY) to all candidate locations. In Hyogo prefecture, seven satellite yards called stock points were placed in the framework of the "promotion work for carrying out/ collecting fallen trees", an operation carried out only by the prefecture, as a gathering point for trees felled by the 2004 typhoon (Fig. 6.1) [137]. According to an interview of the Hyogo Prefectural Federations of Forest Owners' Cooperative Association that was in charge of management and operations, the annual fixed cost of the 6 stock points used over the entire period of the operation was generally within a range of 1 million–10 million JPY. These stock points were implemented to prevent the fallen trees from flooding the standard log market. There are also points that differ from standard satellite yards but for the purpose of this model were regarded as similar as they lack sorting functionality and are merely carrying out log transshipment work. Thus the fixed costs of both types were regarded as comparable. The fixed costs d required over the 5 years of this study were set in 10 stages of 5 million JPY, from 5 million to 50 million JPY, as shown in the next equation.

$$d = \{0.5 \times 10^7, 1 \times 10^7, \ldots, 5 \times 10^7\} \tag{6.8}$$

In the following, "fixed cost" refers to the fixed cost that emerges during the 5 year proposal period in one of the satellite yards.

6.2.6 Numerical experiment outline

The combination of 100 sets of log-producing forest sections and 10 stages of fixed costs results in 1,000 experimental cases. The numerical experiment was conducted using a personal computer with a Intel Core i7-3770k 3.50 GHz CPU and 16 GB memory capacity. The problems were solved using the commercial solver CPLEX12.5

of IBM ILOG [73] on default setting, using the branch and bound method. In the event of setting a time limit to solve the problem and not being able to obtain a suitable solution within the time limit, the best solution found during the search was retained as an approximate solution, as transportation problems with fixed cost are NP-hard mixed integer programming problems [53], and appropriate solutions may not be obtainable within a realistic time frame for large problems. Based on the result of a preliminary experiment conducted to investigate the relation between the calculation time and MIP gap (see below), the time limit was set to 15 min.

Within CPLEX, the MIP gap (%) defined by the following equation is calculated as a standard for evaluating the quality of the solution during the search process.

$$\text{MIP gap} = \text{abs}\left(\frac{\text{Best}_{\text{Int}} - \text{Best}_{\text{LP}}}{\text{Best}_{\text{LP}}}\right) \times 100 \tag{6.9}$$

where Best_{Int} is the value of the best solution, Best_{LP} is the lower bounding value found in the process of searching, and abs $(\bullet)$ is the absolute value. When the MIP gap reaches 0 % the solution is optimal. In this experiment, the MIP gap (%) at the end of the search was recorded.

To derive the reduction effect E of distribution costs obtained by placing satellite yards, distribution F' (of the model without satellite yard placing) was searched for. F' can be obtained by solving the transportation problem of the constraint equation that uses the first term of the objective function of Equation 6.2, constraint Equations 6.4 and 6.6. There are no binary variables in this problem, and since it results in a linear programming problem, it can be solved in a short amount of time using the simplex or interior method.

6.2.7 Placement frequency

In the plan obtained by the numerical experiment for the investigation of suitable satellite yard candidate locations, the frequency that satellite yards are placed $S_m^{d'}$ (%) in candidate location $m \in M$, when the fixed cost is $d' \in d$ was calculated with the following equation.

$$S_m^{d'} = \frac{\sum_{p \in P_{d'}} y_m^p}{|P_{d'}|} \times 100 \tag{6.10}$$

where $P_{d'}$ is the set of problems with fixed cost d', and y_m^p is the binary variable that decides whether to place the satellite yard at m in problem p. $|\bullet|$ denotes the element number of a set.

6.3 Results and discussion

6.3.1 Accuracy of the approximate solution

he average value of the MIP gap in each fixed cost is shown in Fig. 6.3. The MIP gap increased with fixed cost, but remained below 11 % even in the 100 scenarios where the fixed cost had the maximum value of 50 million JPY. While the problems handled in this study were relatively large-scale , with node numbers over 19,000, the commercial solver still succeeded in obtaining approximate solutions within around 10 % of the optimum in the worst case . It was thus possible to obtain a suitable layout of satellite yards rationally positioned from the perspective of minimizing distribution costs.

6.3.2 Reduction effect of distribution costs

Figure 6.4 shows the average of reduction effect E per fixed cost on the left axis, and the average of distribution cost F per fixed cost on the right axis. For ease of interpretation the unit JPY/m^3 is used, dividing the value by the total amount of logs in the model. The average of distribution cost F' (assuming no yard placement) was 4,367.8 JPY/m^3 $\pm$ 20.0 (average $\pm$ standard deviation). It is apparent that reduction effects of distribution costs existed for any fixed cost. A statistically significant difference (p = 0.01) was found between the differences of the average value of F and F' for each fixed cost. This suggests that in the event of the timber center supplying logs only to their factory, and the fixed cost of satellite yards being lower than the 50 million JPY used in the trial calculation, the placing of satellite yards would be effective for the reduction of distribution costs.

At a fixed cost of 5 million JPY the reduction amounted to 930.2 JPY/m^3, 581.6 JPY/m^3 at 20 million JPY, and 375.2 JPY/m^3 at 40 million JPY. Since fixed costs were the only parameters changed, it is obvious that the reduction effect decreased with increasing fixed cost, and became insubstantial at higher fixed costs. This indicates that to increase the reduction effect of distribution costs, it is important to select candidate locations for satellite yards that can keep fixed costs low.

6.3.3 Number of satellite yards placed and distribution

The average number of satellite yards placed reached a maximum of 21.9 when the fixed cost was 5 million JPY, 6.1 at 20 million JPY, and 3.1 at 40 million JPY, showing a decrease as the fixed cost increased (Fig. 6.5). This is due to the fact that the number of candidate locations possessing reduction effects corresponding to the fixed cost went down when fixed costs became high, inhibiting placement. However, even at a fixed cost of 50 million JPY more than 2 satellite yards were placed in all models, and no scenario had zero placements.

Figure 6.6 shows the placement frequency of satellite yards on the map. At fixed costs of 5 million JPY or 10 million JPY, satellite yards were placed in all areas of the collecting range according to the distribution of forest resources (Fig. 6.2). Candidate locations did however become limited as fixed costs increased. Candidate locations showing high placement frequencies were located far from the factory, and were mostly found from the central eastern section to the northern section of collecting ranges with many forest resources. In a practical proposal, it would clearly be effective to preferentially reuse the existing stock point sites around the candidate locations 10, 39, 47, and 66 as satellite yards. The relationship between transportation distance (one–way) from log sources to candidate locations and placement frequency is shown in Fig. 6.7. At a fixed cost of 10 million JPY to 30 million JPY, a significant positive correlation ($p = 0.05$) was found, and placement frequency tended to be high in locations distant from the timber center. When fixed cost was higher than 15 million JPY, only candidate locations with a traveling distance of more than 60 km had placement frequencies of over 20 %. .

The fixed costs of actual satellite yards are thought to vary with the effects of local conditions as well as land prices. However, the above results suggest that it is effective to place many satellite yards in regions where fixed costs are low or in areas with dense forest resources, and that placing satellite yards in areas with high fixed costs and in areas close to factories should be avoided. Additionally, satellite yard placement parameters for minimum distribution cost can change in various ways according to the fixed cost of satellite yards as well as the distribution status of forest resources. Regardless, this study demonstrated that a yard layout proposal that takes such terms and conditions into consideration can be developed using a mathematical programming model.

6.3.4 Amount of logs that passes through satellite yards

Figure 6.8 shows the percentage of the total amount of logs passing through satellite yards in each scenario. Although it reaches 50 % when the fixed cost is over 10 million JPY, the amount of logs passing through satellite yards always exceeds 30 %; regardless of fixed cost, over a third of logs were transported through satellite yards. Since this amount of logs passes through a small number of yards (Fig. 6.5), the average amount of logs passing through one satellite yard became large when fixed costs were high. This was approximately 50,000 m^3 at a fixed cost of 25 million JPY and up to approximately 100,000 m^3 at 50 million JPY (Fig. 6.9). This result shows that if there is a low number of satellite yard placements, the scale of each yard must be increased. It also indicates that care must be used in the selection of candidate locations. Enlarging satellite yards also implies an increase in fixed costs, but the current model used inflexible fixed costs. To increase the realism of placement proposals, it is likely necessary to set an upper limit for the amount of logs passing through based on the local parameters of each candidate location, and to construct a more complex mathematical programming model where fixed costs change depending on the amount of processed logs.

6.4 Conclusions

This study investigated satellite yard layout scenarios using a mathematical programming model, and evaluated the reduction effect of distribution costs obtained by placing yards. The fixed costs incurred by one satellite yard during the model period (5 years) ranged from 5 million JPY to 50 million JPY. Distribution cost-reducing effects of were found in all cases, yet the reduction effect decreased with increasing fixed cost . Larger reduction effects necessitated keeping distribution costs low. A reasonable layout for minimizing distribution costs could be produced by using a commercial solver. In this layout, satellite yards were frequently placed in candidate locations distant from the factory and close to forest resources.

The reduction effect confirmed in this study is merely the result of the log supply activities of one factory, and is based on a number of assumptions. If the model conditions differ (relation of mill and forest resource locations, transportation vehicles etc.), there is the possibility of obtaining strongly varying results. In some cases, even greater effects may be obtained, or no effects in others. When producing a layout proposal for actual implementation, it will be necessary to confirm the existence and extent of any reduction effects and the suggested placement of satellite yards by using a mathematical programming model that appropriately incorporates current conditions.

It is suggested that future research focus on improving the model' realism and the mathematical programming model as well as on realizing distribution routes that conform to reality, so that other characteristics of satellite yards (e.g., profit increase due to inventory adjustment and sorting) may be incorporated in addition to reduction effects of distribution costs.

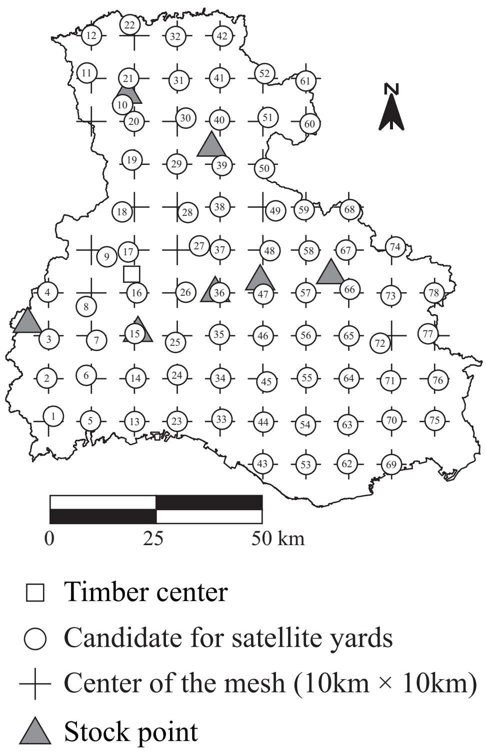

Figure 6.1: Locations of timber center, satellite yard candidate locations and stock points -

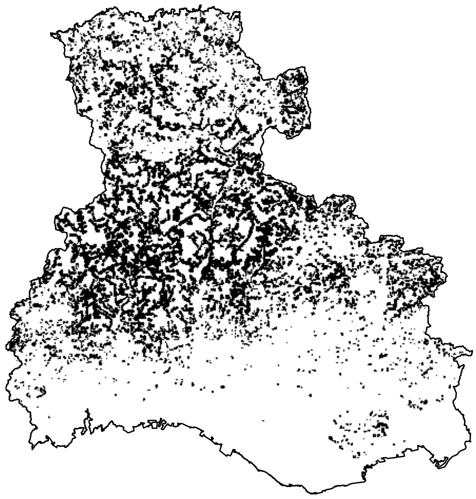

Figure 6.2: Locations of forest section nodes within 300 m of the road - Black dots indicate the forest section nodes.

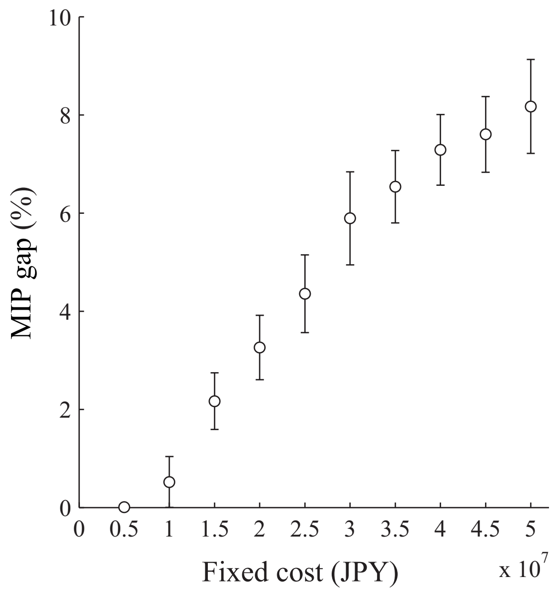

Figure 6.3: Average value of the MIP gap in each fixed cost - Error bars indicate one standard deviation.

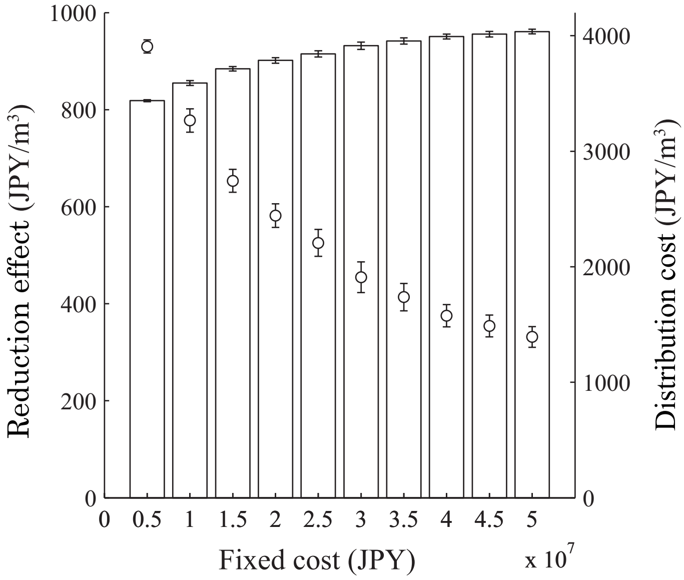

Figure 6.4: Average reduction effect and distribution cost for each fixed cost - Reduction effect are shown on as open circles (left axis), distribution costs as a bar graph (right axis). Error bars indicate one standard deviation.

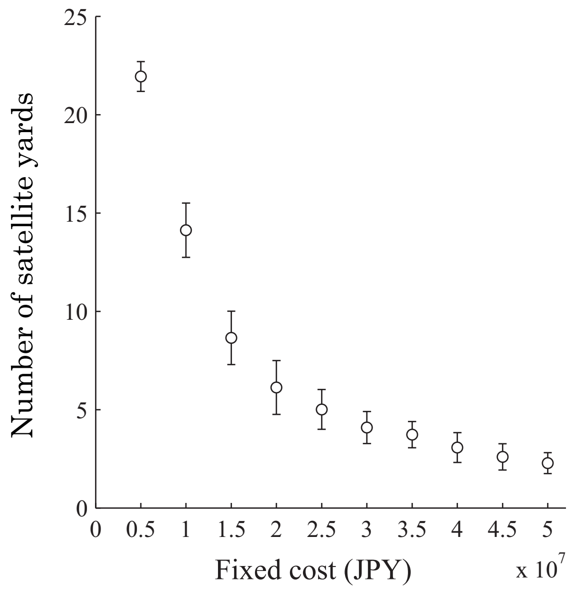

Figure 6.5: Average number of satellite yards placed for each fixed cost - Error bars indicate one standard deviation.

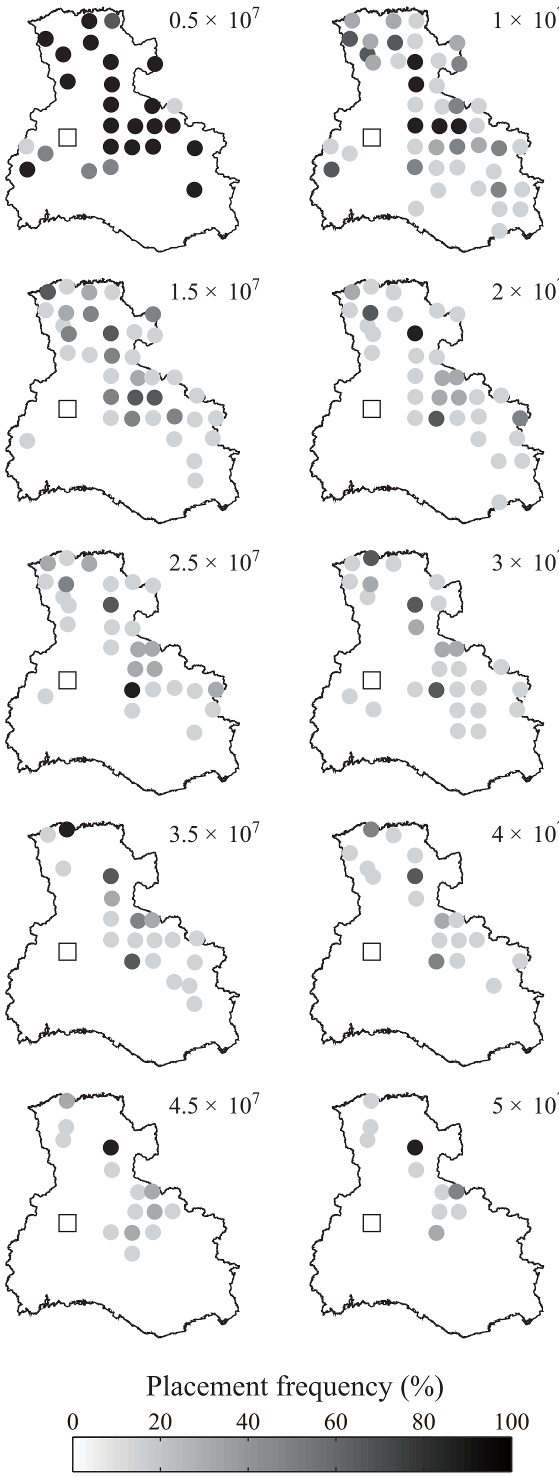

Figure 6.6: Frequency of satellite yard placement for each fixed cost - Candidate locations are shaded by increasing frequency. Fixed costs (JPY) are shown above maps.

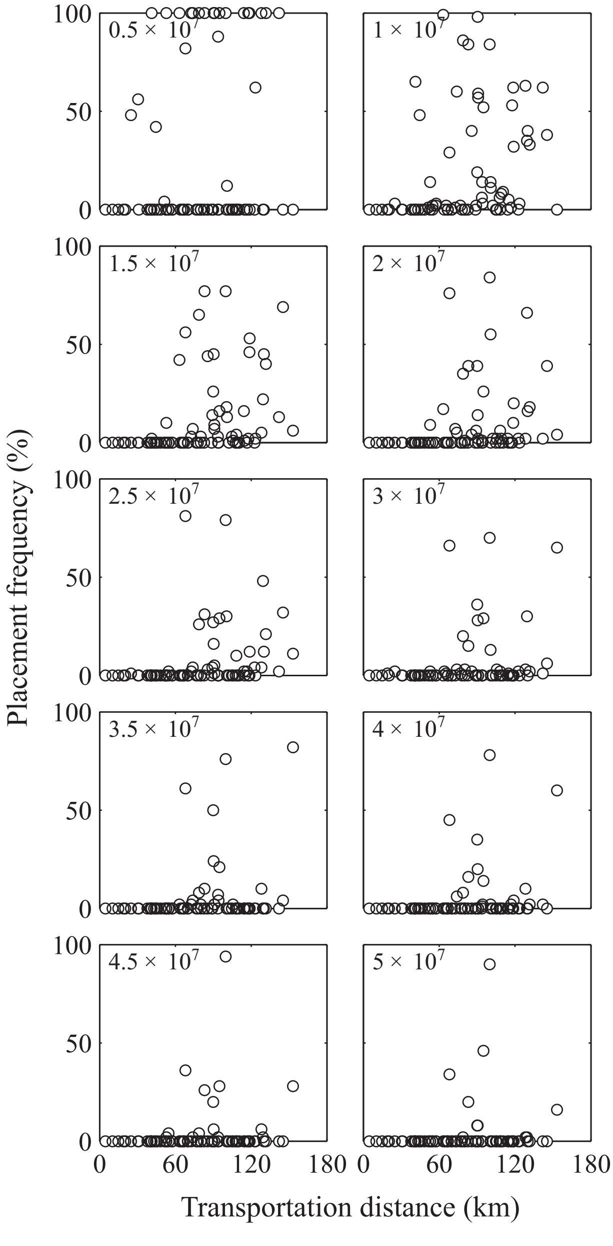

Figure 6.7: Relationship between transportation distance and placement frequency - Fixed costs (JPY) are shown in each graph.

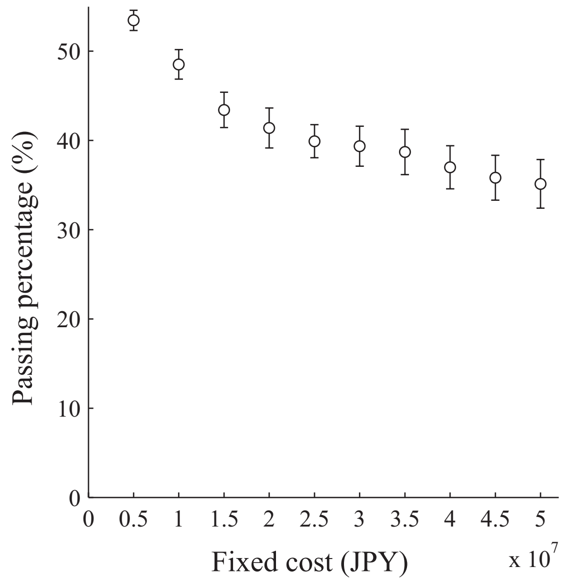

Figure 6.8: Average percentage of total amount of logs passing through satellite yards - Error bars indicate one standard deviation.

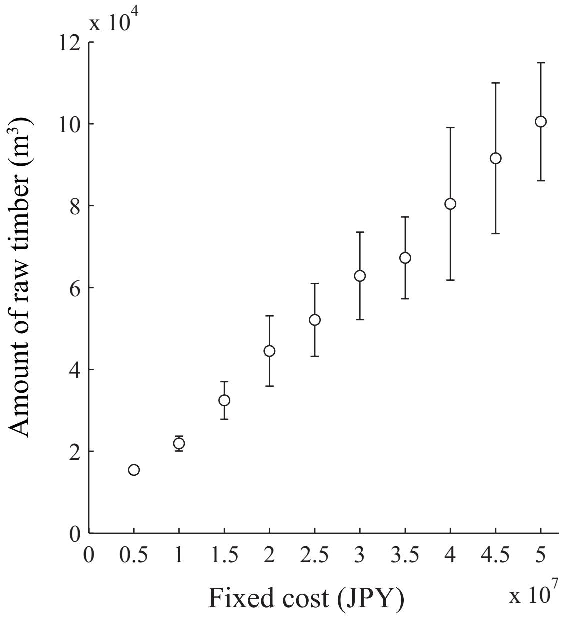

Figure 6.9: Average amount of logs passing through one satellite yard - Error bars indicate one standard deviation.

7

Concluding chapter

7.1 Summary of results

This thesis discussed operational forest planning problems in relation to road network layout, cable corridor layout and timber transportation. Each chapter is summarized below.

In Chapter 2, a comparative study of the performance of heuristic algorithms for the multiple target access problem (MTA) was conducted using computational experiments. MTA requires the minimum cost road network accessible to given targets on forest land to be designed via the construction of new roads from existing road networks. We first show that by identifying nodes representing existing road networks, MTA can be transformed into the Steiner tree problem (ST) in graph theory. This allowed us to use ST algorithms for solving MTA. Because STP is NP–hard, heuristic algorithms were applied. In the computational experiments, each of 14 heuristic STP algorithms, several of which had twice the optimal performance level, solved 1,120 MTA instances with various properties. Results indicate that the average distance heuristic (ADH) and repetitive applications of the shortest path heuristic (SPH-V, SPH-Z, SPH-zZ and SPH-ZZ) exhibited consistently superior performance in terms of solution quality. It was also confirmed that ADH, SPH–V and SPH–ZZ design similarly shaped road network layouts.

In Chapter 3, the problem of designing road networks suitable for timber harvesting operations was considered. It is shown that this problem can be formulated as the directed Steiner tree problem (DST) when the objective is to minimize the sum of road construction costs and skidding / yarding costs. A principal feature of the formulation is the intention to design minimum cost road networks where harvesting machinery can efficiently harvest timber resources in a planning area, without rigorously laying out a concrete location of harvesting machinery or landings. Several new heuristic algorithms based on density or cost–benefit analysis are proposed in this regard. To compare the performance of the proposed heuristic algorithms to that of some existing heuristic algorithms for DST, computational experiments where realistic problem instances are solved and then road networks are designed according to specifications for road design and harvesting operations are also presented. The results of the experiments confirm the high performance of the proposed heuristic algorithms in terms of solution quality.

In Chapter 4, the most profitable cable corridor layout (CCL) is solved by formulating the CCL as a k–directed Steiner tree problem (k–DST). By introducing a parameter k, unprofitable timber stands can be eliminated from the currently projected operations. Here, we evaluate the performance of two existing k–DST approximation algorithms, Takahashi–Matsuyama (TM) and Charikar's algorithms, by conducting computational experiments. The results of our experiments demonstrate that the Charikar's algorithm outperforms the TM algorithm unless all the timber stands in a planning area are yarded. Moreover, because our formulation operates on timber stands only when economically feasible, it yields more profitable layouts than the previous formulation.

In Chapter 5, the effect of selecting the type of transportation vehicle on transportation costs in a roundwood supply chain is verified. An estimation of transportation costs was conducted assuming appropriate transport routes for four differently-sized vehicles (2 ton, 4 ton and 15 ton trucks and 24 ton trailers). Cost reductions of the combined application of 2 t and 4 t trucks were an average of 1616.4 and 553.0 JPY/m^3 compared to single applications, respectively. The application of a 15 t truck and 24 t trailer via a satellite yard reduced costs by a further 812.9 JPY/m^3. It was shown that selecting a suitable vehicle for each logging area and using large vehicles for long-distance transport can effectively reduce transportation costs.

In Chapter 6, satellite yard layout planning was examined through timber procurement activities by a large-scale sawmill in Hyogo prefecture, and the reduction effect of satellite yards on distribution costs was approximated. Satellite yard layout plans were generated using a mixed integer programming model. At least two satellite yards were placed in each scenario. The reduction effect of satellite yards on distribution costs was

930.2 and 581.6 JPY/$m^3$when fixed costs per satellite yard in a planning horizon of five years were 5 million and 20 million JPY, respectively. The results show the presence of cost reduction effects of satellite yards and also suggest the importance of keeping down fixed yard costs to enhance this effect.

7.2 Concluding remarks and future work

In this thesis study, it was demonstrated that planning problems concerning forest road networks and cable corridor layouts can be formulated as the Steiner tree problem and its generalization. Heuristic algorithms were described and applied to solve each problem, and their performance compared through computational experiments in which realistic assumptions about the underlying planning tasks were made. Several new heuristic algorithms providing high performance in terms of solution quality were proposed for forest road network design problems incorporating timber harvesting operations. In accordance with the fact that the timber transportation problem can be formulated as the fixed charge transportation problem, the presence of cost reduction effect of large vehicles and satellite yards was also verified. This study enabled carrying out a series of operational forest planning tasks, where road construction, timber harvesting operations and timber transportation were determined with spatial detail.

Forest managers and engineers address a wide variety of forest planning problems, and in the process they must make a number of decisions. A formulation which describes forest planning problems with a formalized mathematical language enables the application of mathematical theory and algorithms, and is thus better able to represent the inherent structure of a problem and to facilitate rational decision making. It is suggested that future research expand the set of forest planning problems for which suitable formulations have been provided. For example, the problem of designing road networks with cycles or multiple road standards has not yet been formulated.

Forest planning problems are not necessarily solvable just because their formulations are available. Unfortunately, they generally belong to (or are expected to belong to) the complexity class of NP-hard problems, as is the case with the problems dealt with in this thesis. Future research might therefore also focus on the development of heuristic algorithms specialized for solving individual planning problems.

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Chapter 3

Title: New heuristic algorithms for designing forest road networks suitable for timber harvesting operations

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Chapter 4

Title: Cable corridor layout problem in cable yarding operations: Formulation and solution using graph theory

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Chapter 5

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Chapter 6

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