ISSN: 2454-9940

INTERNATIONAL JOURNAL OF APPLIED SCIENCE ENGINEERING AND MANAGEMENT

E-Mail :
editor.ijasem@gmail.com
editor@ijasem.org

www.ijasem.org

INTERNATIONAL JOURNAL OF APPLIED SCIENCE ENGINEERING AND MANAGEMENT

ISSN2454-9940www.ijsem.org
Vol 5, Issuse.3 Sep 2017

Future Directions in Transportation Engineering and the Development of Forest Road Networks

Dr.Suresh M, Saba Faranaz, Laxmi Sunaina

Abstract

This study synthesizes separate but related developments in the fields of conventional and computer-assisted methods for planning road networks. The study's principal conclusion is that significant theoretical progress was sparked by changes in how the road network architecture challenge was conceptualized. It wasn't until the 1870s that a unified, two-dimensional (2D) transport geometry representation evolved, allowing for the mathematical derivation of optimum road spacing. In the early 1970s, a change in how problems involving road networks and crop layouts were represented was sparked by the formalization of these issues as mathematical graphs and the subsequent solution of the accompanying linear programming problems. A further representative development occurred at the beginning of the 1990s, when digital elevation models DEMs were widely available, making it possible to automatically construct up road networks on the DEM surface of the underlying topography. The most recent change was in the mid-1990s, when systems began to semi-automatically map out harvest/transport-network difficulties on DEMs. The paper presents challenges for future research, the most pressing of which is the development of the concurrent harvest/road-network layout systems for multi-objective functions. Since improvements in problem representation tend to go hand in hand with scientific progress, it's important to study new ways of representing lattice-type terrain. Triangular irregular network (TIN) meshes are now the most intriguing of these alternatives. Some other potential avenues for development include the combination of road network planning and detailed road engineering, the elaboration of optimization problem formulations, and the universal modification of road network planning curricula to incorporate operations-research-based strategies..

Keywords: *road network, network layout, road spacing, road density, computer-assisted net-work layout*

Introduction

The success of the timber industry has been built on a road system that follows fundamental design principles. Since their inception, these tenets have evolved with the development of science and the improvement of on-road and off-road vehicles. There is a wide variety of scientific ideas at play here. The cutting edge of development in plantation forestry settings is computer-assisted systems that automatically generate the concurrent arrangement of roads and harvesting systems (Epstein et al. 2006, Epstein et al. 2001). On the other hand, training programs for forest operations professionals still include conventional expert techniques that depend on the abilities and expertise of the designers. Google Scholar reports that there have been roughly 70 scholarly articles published on the topic of forest road network design since 1960, however this does not indicate that the topic has been fully explored.

Assoc. Professor[1] ,Asst. Professor[2,3]
Department of IT
Dr.m.suresh.m@gmail.com, saba.faranaz@gmail.com, sunainalaxmi12@gmail.com
ISL Engineering College.
International Airport Road, Bandlaguda, Chandrayangutta Hyderabad - 500005 Telangana, India.

there has been no systematic assessment of current understanding. Review studies (Church et al. 1998, Epstein et al. 2007) summarized the state of knowledge for mathematical methods based on operations research methodologies, whereas traditional texts and handbooks (Dietz et al. 1984, Hafner 1971, Kuonen 1983, Wenger 1984) recorded expert-based approaches.

The objective of this contribution is to unify computer-aided and conventional road network layout methods and to provide a broad outline of the direction of progress. Most specifically, it hopes to:

Timely disclosure of ideas and procedures for various conceptual approaches

Determine breaks, or points of significant change.

Forest road networks are the only subject of the following introspections; other low-traffic road systems are ignored. They'll even make up for the lost

cover the time period beginning with the publication of the first scholarly studies on forest road networks at the tail end of the 18th century and ending with the present day. Before diving into an analysis of the transport geometry method that led to the idea of optimum road spacing, the article will provide a brief overview of the historical background up to World War I. And third, it will examine the evolution of the semi-automatic computer-aided road network planning approaches that were first created using operations research techniques. Finally, we'll go through how to plan a road system and a harvesting system using a computer program.

Early Developments

Good road design methods have contributed to the growth of the forest products industry. As time has progressed, so have our understanding and application of these concepts, as well as the capabilities of on- and off-road vehicles. Different scientific paradigms are in play. The most cutting-edge technology in plantation forestry are computer-aided systems that can generate the simultaneous layout of roads and harvesting equipment (Epstein et al. 2006, Epstein et al. 2001). While modern techniques are increasingly emphasized in training programs for forest operations specialists, conventional expert approaches that depend on the knowledge and abilities of the designers are still a component of the curriculum. According to Google Scholar, there have been around 70 scholarly articles published on the subject of forest road network design since 1960. However, this does not necessarily indicate that sufficient study has been conducted on the matter.

Lacking is a thorough assessment of where we are in terms of knowledge. Expert-based procedures were documented in classic manuals and handbooks (Dietz et al. 1984, Hafner 1971, Kuonen 1983, Wenger 1984), while the state of knowledge for mathematical methods based on operations research methodology was summarized in review studies (Church et al. 1998, Epstein et al. 2007).

This contribution seeks to standardize methods for both automated and hand-operated road network design, while also drawing attention to promising directions for further research. And its specific goals are to:

Timely and accurate technique and idea disclosure for a wide variety of conceptual approaches

Seek for the gaps, or the places where there is a significant departure.

Only forest road networks are considered here; no other low-traffic road systems are included. Eventually, they'll make up for all that was lost. include all of time from the late 18th century, when the first scholarly studies on forest road networks were published, to the present. Prior to delving into an analysis of the transport geometry method that led to the concept of optimum road spacing, the article will provide a brief overview of the historical circumstances leading up to World War I. Finally, it will detail how operations research was instrumental in the creation of semi-automatic computer-aided road network design ideas. The tutorial will conclude with a discussion of how to utilize a software tool to plan a road network and a harvesting network.

Location theory and transportation economics may trace their roots back to von Thünen's seminal book »The Isolated State concerns Agriculture and Political Econo- my...« (Thünen 1842). Thünen analyzed how different types of land use were distributed in and around a city with little to no economic activity. Under these suppositions, different types of land use cluster together to create concentric spheres. After doing some research, he came to the conclusion that cutting down trees for lumber should be done in a different sector. Beyond a radius of around 8 miles, the increased expense of transportation would have made the wood reward too little to justify the effort. To give you an idea of how taxing land transportation was back then, consider that one unit of horse and carriage could deliver approximately two cubic meters of firewood and traverse around twenty to thirty kilometers in a day.

The introduction of widespread railway networks about 1840 marked a turning point in the evolution of transportation infrastructure. This development greatly reduced the price of land transportation, which facilitated the trading of products over great distances. Quantitative approaches for the design of transportation networks began about 1860 with the emergence of the idea of transport network layout, which developed independently in Germany and France (Lalanne 1863, Launhardt 1872). To determine the optimal topological network configuration, both authors proposed a new step of design, currently known as the "architecture establishing an interconnected system between all of the »transport points. Taking into account technical restrictions and yielding a smooth horizontal and vertical alignment is the goal of the subsequent detailed road route engineering phase, also known as the »design definition process« (Walden et al., 2015), which Launhardt referred to as the »technical trace«. The lasting effects of this landmark study on the philosophy of forest road network design are unclear. Later textbooks still include some of the earlier concepts on conceptual design, such as the specification of »transport locations« (»fixed points«, »control points«), and the search for a network topol- ogy (Dietz et al. 1984, Hafner 1956, Kuonen 1983, Wenger 1984). To the best of our knowledge, the first textbook to provide a full discussion of forest road networks was »Forest Road Construction and Its Preliminary Work« (Schuberg, 1873). The author understood that the challenge of transportation planning in the forest sector was not one of connecting specific points but rather of making the whole region equally accessible. Although Schuberg's analytical solutions may not be correct, yielding an ASD of 5/24 road spacing, which is quite close to the correct solution of 1/4 road spacing, he nonetheless introduced the principles of forest transport geometry and quantified the relationship between road spacing and average skidding distance ASD. For flat terrain, he definition process" (Walden et al., 2015). The urban transportation system first identified high-volume traffic nodes and then sought the most efficient route between them. Launhardt used a quantitative approach, whereas the French method was strictly geometric. When he was in the conceptual design phase, which he dubbed »commercial trace« (Launhardt 1872), he completely disregarded topographical conditions in order to build the optimal network arrangement on a flat plane. His method began with the identification of »transport locations« (cities, towns, production sites) and the unique traffic patterns they exhibited. The challenge then became figuring out how to go from one place to another with the fewest number of stops and the cheapest possible transportation. Taking into account traffic patterns and the geometry of the surrounding intersections, he devised a method for determining their ideal placement. As a whole, Launhardt's approach produced a Steiner tree,

recommended a lattice of roads, with an average road spacing of up to 700 m if a secondary network of skidding roads is also present. For example, »contour-type networks« are a special kind of network that emerges when the terrain places restrictions on where routes may go. To use Launhardt's terminology, the conceptual structure of forestry road networks was determined by those factors. Reliable contour maps were required for the comprehensive road network planning, and it was previously known how to use a compass to plan roads with a constant gradient by stepping from one contour to the next at a consistent distance. After a satisfactory answer was established on the map, surveying devices were used to translate the design to actual route places in the landscape. Because other textbooks were primarily concerned with road engineering and road building, it is unclear how Schuberg's methods gained traction and expanded (Stoetzer 1877, Stoetzer and Hausrath 1913). In North America, the necessity for economic rationalization and a knowledge of logging cost accelerated the formalization of road network and transportation engineering around World War I (Greulich 2002). A second break in progress occurred after the 1920s, when motor vehicle-based transportation systems saw a boom as a consequence of the First World War. This yielded quantitative insights that we shall examine later.

Optimum Road Spacing/OptimumRoad Density

oss several time periods

As a consequence of Taylor's groundbreaking work on time studies (Taylor 1895), industrial engineering emerged as a scientific subject, leading to a better knowledge of production cost and productivity. There were more studies of costs and times involved in forest operations because of it (Ashe 1916, Braniff 1912). The introduction of the tractor for use in skidding operations at the end of the 1930s vastly expanded designers' palette of possible forest harvesting system configurations. Because of this new degree of variation, an operational study (Mat- thews 1939) concluded that, depending on road conditions, the cost of off-road transportation was anywhere from six to nine times higher per unit of volume and per unit of transportation distance than the cost of on-road transportation. The data led to the conclusion that there is a minimal level of reduction in total cost that may be achieved by raising the percentage of on-road transportation while lowering the proportion of off-road transportation. Matthews, in his fundamental study (Matthews, 1939), posed the issue of what road spacing would provide this minimum. Because of these presumptions, he was able to create a model of transport geometry: road construction costs are constant, since the forest region has a flat, homogeneous topography; off-road transportation expenses vary solely on the distance traveled.

There are no connections between the roadways, and the road structure resembles a grid.

There is only one forest management method that can be used to the whole region; the road network is constructed all at once, and there is no sequencing between the acre loading point in the stand and the landing point on the road. The forest stand conditions are consistent throughout the board.

Some correlations, such as the one between road length and road spacing for a unit area, emerged implicitly in Matthews' (Matthews 1939) mathematical formulation, which is not easy. For this reason, a clearer expression is provided below. The transport geometry model shown in Fig. 1 is primarily comprised of road spacing (sr) and road length (L). So long as sr and L together cover exactly one square unit, sr is the unit of measurement for road distance in Australia

developed generalized cost functions for both road construction and off-road transportation, using the basic relationships of (4) and (5). He relaxed the assumptions of a purely parallel road network and the shortest off-road transportation path by introducing correction factors, which he investigated for different geometrical extraction patterns. He then extended (8)

The pattern of extraction for a lattice-style network is shown in Fig. 2. A pattern of 8 triangles per unit area is produced if logs are assumed to be travelling along the shortest route to the closest road, and the average skidding distance for a single triangle is equal to the distance from its centroid to the nearest road, which is one third of the road spacing sr (13).

using those adjustments to get the best possible road distances. As a result of his efforts, studies like one that sought to determine the best route to take in a given situation were conducted.

main and secondary road networks' spacing and alignment (Larsson 1959). Segebaden (1964) looked into what would happen if we loosened the assumption of parallel highways and the shortest off-road transit route.

For triangular, rectangular, and hexagonal networks, the ratio of the effective to the theoretical average skidding distance (14) is 1.33. (Segebaden 1964). Mathematician Matern examined a Poisson distribution.

field network showing that the appropriate cnet correction factor for Segebaden is precisely 2.0.

The primary considerations are outlined in (17), which provides a

The Segebaden network correction factor cnet was included in the skidding cost term of the total cost function (6). He also suggested a correction factor for off-road transport (coffr) to account for the fact that logs do not always follow the quickest route to the next road. When we take into account both cnet and coffr, we get a more generic cost function (16).

reducing the road network's economic efficiency. Low road spacing is required by ineffective skidding technology, which in turn increases the importance of the ratio of road building cost to skidding cost (cr/cs). High values of the network correction factor cnet, which represent inefficient road network geometry, have a comparable impact. Road spacing is decreased to around 70% of the original value using a Poisson field layout, which results in a network correction factor of 2.0 (see Sege- baden).

reduced to a system of roadways running parallel to one another. High road densities are the result of a risky capital budgeting strategy (low interest rates), whereas low-risk budgeting policies (higher interest rates) result in closer road distances.

Investments in expanding a city's road network should be seen from the perspective of capital budgeting, which involves balancing the project's expected costs and revenues throughout its expected lifespan. This long-term investment consideration is ignored in the optimum road spacing (8) and road density (11) formulas. The total cost of an asset may be easily estimated using the EAC technique, which is calculated by multiplying the asset's yearly operating costs by the asset's useful life. Assuming the road network is in good condition,

policies (high interest rates) lead to wider gaps between roads. Last but not least, the volume of harvesting flows is a measure of management intensity that is influencing road density. Road spacing is around half what it would be under traditional forestry regimes within an annual flow of approximately 7.5 m3 per hectare as compared to a plantation forestry regime with an annual flow of about 30 m3 per hectare. Those aren't very novel realizations, but you shouldn't take them for granted.

Given that the job has a 50-year lifetime and a reasonably low interest rate of 2%, the annuity factor is 3.18%. The amount of interest due may be prohibitive if it were to

In a scenario where capital is not properly budgeted for, the annuity factors rise to 2.0%, resulting in a 35% increase or decrease in the cost of the road's construction. An annu- ity and yearly maintenance factor were the first to be used to indicate maintenance expenses as a percentage of initial expenditure in the United Kingdom (Gayson 1958). The harvesting volume V, measured in volume units per area unit, must be translated into an annual harvesting flow volume Va, equal to the mean annual increment under steady-state assumptions, in order to make the total cost function con- sistent. The equation for the generalized optimum road spacing (17) is produced by including the capital budgeting considerations into the total cost function (16), computing the derivative with respect to road spacing sr, setting it to 0, and solving for sr.

As the inverse issue of optimum road spacing, determining the ideal road density may be expressed as [18]. The International Labor Organization (ILO), the Food and Agriculture Organization (FAO), and the United Nations Economic Commission for Europe (UNECE) convened a symposium in 1963 in Geneva, Switzerland, to discuss the establishment of forest communication networks. Nearly all of the era's forest operations engineers took part, pooling their expertise to discuss how best to build a road system from many vantage points. Sundberg presented a study on the economics of road networks, which surveyed previous research in the field (Sundberg 1963). He underlined that the effective distances are greater than the theoretical distances since both the network correction cnet and the off-road transport correction coffr factors multiply with the theoretical average skidding distance. He went on to explain why this factor should be included in the calculation of road density and spacing.respectively. Silversides gave an overview on the influ- ence of logging methods on the road network layout (Silversides 1963). He emphasized that Matthews book (Matthews 1942) still build the basis of the North American approach to estimate optimal road spacing, thus neglecting some of the newer Swedish achievements. He requested that future work on road spacing should distinguish two cases:

- systems where the logs are moving on the shortmost direct route to the closest road — systems in which logs are transported to designated transhipment locations (landings) spaced at regular intervals.

Matthews's key work, »Cost Control in the Logging Industry,« from 1942, proposes a method for calculating road and landing spacing at the same time. The average yarding distance is no longer the same as the distance from a region's center to its closest road if the logs are instead assumed to be moving along a radial axis toward the landing. As a result, a report was published with a more accurate assessment of the typical skidding distance (Suddarth and Her- rick 1964). A little more accurate than Matthews' approximation, Peters' later method is yet difficult to solve. Interestingly, Segebaden's network correction factor cnet, which measures the impact of inefficient road network structure, was never taken into account. Therefore, the port geometry of parallel roads was assumed by all the approaches that used concurrent landing/road spacing (Fig. 1). Landings have traditionally been assumed to be situated on access lines that run perpendicular to highways in traditional geometric designs. Bryer relieved the pressure of this assumption by relocating the landing spots every other road (Bryer 1983). Based on the data, it was determined that a landing-to-road spacing ratio of 1.5 to 2.0 results in an average skidding distance reduction of 5 to 9 percent while shifting.

Efforts to improve the most efficient and cost-effective configuration of road systems waned in the 1970s. While some studies modified the cost function by including in things like worker travel time and the potential cost of development lost owing to aisle clearance (Abegg 1978), the vast majority of studies adapted the function to local conditions. There were other dubious contributions, including include overhead expenses in the best road spacing calculation (Thompson 1992). One may isolate the factors that are directly related to road spacing by formulating a total cost function and locating the derivative for road spacing. Overhead expenses should not be formulated as a direct function of road spacing in an overall cost function.

Models of transportation geometry were flat (see Figures 1 and 2). Using a 3D-model, researchers may examine the effects of slope on the road network architecture and the rise in total cost function for a mix of road and off-road transportation. Heinimann came up with a method to tell the difference between skidder and cable-yarder-based road network ideas on steep inclines (Heinimann 1998). He discovered that the total cost function for using a skidder was lower than using a yarder on a gradient of 30%. Inversely, at a slope of 50%, the yarder-based operation outperformed the skidder-based one. Therefore, there must be a sloping threshold beyond which the cable-based system is more efficient than the yarder-based one. This method may be adjusted for various road network paradigms provided relevant context data is made accessible. Previously, conventional wisdom served as the primary basis for differentiating between various road network designs.

OR-Tool-Supported Road NetworkLayout

The quality of solutions developed is dependent on how problems are presented, according to a high-level group on decision-making and problem-solving (Simon et al. 1986). The post-computer age began in the 1950s, allowing people to tackle previously insurmountable challenges. For this reason, linear programming has begun to find widespread use in business contexts, since it offers tools for finding the best course of action given a system represented by a collection of linear connections and subject to linear inequality or equality constraints. It's not hard to understand how this branch of math and science began to set off new ways of thinking about forest engineering and management. Operations research approaches in forest engineering owe a great deal to a conference held in Oregon in 1973 on »Planning and Decision-Making as Applied to Forest Harvesting« (O'leary 1972). Two papers discussed the use of OR-methods to road network design (Kirby 1972, Mandt 1972). You may see the problem representation (shown in Fig. 3) that was used to develop the corresponding mathematical program.

To some extent, the assumption that the forest cover is uniform over the whole region of interest may be relaxed thanks to the depiction shown in Fig. 3. Similar units (stands, harvesting units, timber strata) are split up over the land and managed in accordance with the area's predetermined silvicultural regime. This depiction further removes the restriction that all road construction must occur simultaneously, making it possible for individual road sections to be created at any moment. A single access node (N1-N8) is assumed to be present in each forest unit in the conceptual model (Fig. 3), from which the whole forest unit may be controlled. It also specifies the road segments (S03–S67) that connect the nodes and facilitate the transport of wood from the origin nodes (N1–N7) to the destination node (S) (N0). Mandt (1972) proposed the study of road networks from a network analysis viewpoint, building on the previous work of Kirby (1972) on problem formulation choices (Ford and

Fulkerson 1962). The formulation and solution approach for the planning issue shown in Fig. 3 were given in an influential study (Weintraub And Navon 1976). The authors established categories for (1) access nodes I, (2) road segments J, (3) epochs T, and (4) wood types K. The goal is to schedule all harvest units (i1...in) and necessary road segments (j1...jk) during the time periods (t1...tl) in a way that maximizes the discount (revenues minus costs). This aim can be easily transformed into an objective function, but defining the necessary restrictions is more challenging. The authors arrived at a formulation that could be solved in roughly 2 minutes and fifty seconds using a mainframe computer (Weintraub And Navon 1976). The number of roads in the solution could not exceed the number of shortest pathways between access and sink nodes (Kirby 1986). Large-scale network challenges, such as those involving multiple connections and several road building and reconstruction projects, may be described and addressed using the conventional transhipment problem formulation (Kirby et al. 1979). By the start of the 1980s, this framework had evolved into the integrated re-source planning model (IRPM) and was being put into use by the
Service of Forestry in the United States of America. In place of wood classes, this model considers different land-use scenarios and defines traffic capacity in terms of sets of traffic flows. Heuristic solution procedures based on a series of the linear program run were necessary to solve the model, and this was only possible for problems of a modest magnitude (Kirby 1986). The authors knew that such a heuristic approach would never, ever, provide optimum designs save by pure chance.
Locational difficulties in forest management: a literature review discusses the present status of models for coordinating harvest and road network design (Church et al. 1998). The challenge is significantly reformulated as modeling »the scheduling/location which harvest units will be cut in each period, fulfills adjacency criteria, and guarantees that no unit is harvested without the full road route that may reach the unit. The authors also covered the wide range of approaches used to tackle these issues, including: dual ascent; Lagrangian heuristics; Monte Carlo integer programming; simulated annealing; and tabu search. This multiple target access problem (MTAP) was formally outlined in a subsequent study (Murray, 1998), which stressed the need of basing an accurate solution strategy on the Lagrangian relaxation with branch and limit.

The integrated formulation of harvest/road-net- task plan and scheduling allowed for a thorough evaluation of harvesting expenses, including travel costs and the cost of constructing and maintaining roads, as well as a scaled-back relationship between the two. While this is helpful, it still requires some forward thinking on the part of the planner.

Connectivity Hubs

road section locations between access points

locations on the landscape

a comprehensive plan for harvesting activities outside the range of each access point.
Computer-Aided Road Network LayoutPlanning
Contour maps built – since their emergence in the Renaissance – the backbone for any spatial planning activity, such as road network layout or harvest planning. By the end of the 1950s, a master thesis at MIT proposed digital terrain models (DTM) as an alternative to contour maps (Miller 1958). A digital terrain model approximates a part of the continuous terrain surface with a large number of selected discrete points with known XYZ coordinates in an arbitrary data co-

pended on the skills and experience of the planner, resulting mostly in sub-optimal solutions, compared to the optimum.
Graph theory knows the concept of the minimum spanning (Weisstein online-*b*) tree to connect all the nodes with the minimum possible total link weight, which can be cost or any other metric. It is easy to see that the automatic solution presented in Fig. 4 is a type of minimum spanning tree. The insight that access nodes could be connected by a minimum spanning tree appeared already in the 1960s in the literature (Kanzaki 1966). The solution in Fig. 4 is a Steiner Minimum Tree (Weisstein online-*c*), which introduced additional »Steiner points« to improve the minimum spanning tree solution in the best possible way. There are two algorithms to solve the minimum spanning tree problem, Prim's (Prim 1957) and Kruskal's (Kruskal 1956). While there is no exact solution for Steiner tree problem, good approximations are available (Rob-

ins and Zelikovsky 2000).

So far, we discussed some options on how to automatically identify a solution and connect nodes into a directed graph. However, the issue of how to automatically layout a road between two nodes on a digital elevation model still needs a solution. A digital elevation model is a discretization of a continuous,

tends to result in a chain of consecutive straight lines without any curve or switchback constraints. The two concerns triggered the investigation of alternative link-patterns (see Fig. 5, right) and of horizontal alignment restrictions (Stückelberger et al. 2007). It demonstrated that the link pattern specification heavily influences road network locations and alignments. The main result was that the 24 link-pattern model that penalizes switchbacks yields good solutions for slope gradient of up to 30%. Steep terrain requires both the refined link model (e.g. 48 links per node, Fig. 5, right) and the introduction of horizontal curvature constraints. The introduction of curvature constraints increases the size of the graph representation by a factor of 256, resulting in a substantial increase in computing times. The authors found that the 8-link zigzag is not always able to identify road segments between 2 points in steep terrain, whereas the 48-link pattern always did so. They found that cost lower by about 30% for the 48-link model in steep terrain, and by about 10% for a constraint 8-link model in moderate terrain (Stückelberger et al. 2007), both compared with the unconstraint 8-pattern. Another investigation developed a model to estimate the spatial variability of road construction cost for a specific area of interest, based on geotechnical information and parametric cost modelling as used in the construction industry (Stückelberger et al. 2006a). Road network layouts based on the assumption of route-independent construction cost resulted in a 10% shorter overall road length but in an increase in road construction cost of about 20% (Stückelberger et al. 2006a) compared to route-dependent cost assumptions. The study further demonstrated that cost-estimating procedures that consider only slope gradient are still resulting in a 20% lower total construction cost compared to the route-independent cost alternative. Based on the work presented above, computer-aided engineering approaches for the layout of forest road networks under difficult terrain conditions reached some maturity, based on which future tools and solutions can be built.

Computer-Aided, Concurrent Harvest Road-Network Layout Planning

The plant (harvest) location issue and the road location problem, both of which must be represented in a massive network with hundreds of thousands of nodes and millions of edges, are two NP-hard problems that must be solved simultaneously by computer for the optimal harvest/road-network structure (Epstein et al. 2001). In the 1970s, Weintraub and Navon proposed a general solution based on the conceptual model of Fig. 3, but they neglected to take into account the harvest layout activities needed to harvest and extract the wood to the input nodes, which they called access nodes. As a result, it is necessary to use the spatially explicit harvest layout model, which was first introduced in a landmark study in the 1970s (Dykstra And Riggs 1977). A spatially explicit design model does this by subdividing the study area into a grid of quadratic cells, which are then often placed on a digital elevation model. Therefore, the challenge is to define ground-based and cable-based extraction zones, as well as transhipment locations (landings) for tower yard- ers and skidders, such that the greatest number of cells may be reached at the lowest possible cost (Church et al. 1998). It is essential that the terminals for a specific road network be situated along those roadways. In addition, the structure of the concurrent harvest and road network attempts to link all the transhipment nodes to the final destinations.

The solution to the simultaneous harvest/road-network-layout challenge was pioneered by Chilean operations researchers Weintraub and Epstein, with input from Bren and John Sessions (Church et al. 1998). Fondef, a Chilean government organization, began providing funding for the creation of fundamental operations research instruments for the Chilean forest sector in 1993. All of the following choices must be modeled in order to solve the concurrent layout issue.

How much land should be set aside for each cable system configuration; What roads should be constructed; How much wood should be harvested and transported; Which areas should be harvested by ground-based and cable-based systems; (Epstein et al. 1999).

When the most well-known systems for making such judgments, PLANS and PLANZ (Cossens 1992, Twito et al. 1987), were evaluated and shown to be underperforming, they prompted the creation of PLANEX to address the concurrent layout issue. Topographic data of the harvesting region, including wood inventories at an appropriate spatial resolution, was needed for modeling the issue. PLANEX was built to work with a geographic information system.

The formulation and solution of the model are explained in further depth in another study (Epstein et al., 2006). A large-scale network design model was created using data stored in cells 1010 m in size, and the modeling methodology was inspired by mixed-integer linear programming. The suggested 24-link arrangement is quite similar to the 16-link pattern shown in Fig. 5. The method also takes into account horizontal alignment restrictions, especially turn radii. The model includes a large number of sets, parameters, and variables, and it is used to reduce costs associated with building roads, setting up machinery, harvesting crops, and transporting them. There are typically over 75,000 wood cells, 400,000 possible road segments, and around 300 transhipment stations for cable systems and 5000 for ground-based systems involved in the average issue. The problem-solving approach is analogous to a heuristic for identifying Steiner Minimum Trees (Weis- stein online-c), and it yields answers that are just 3.5% off from the precise solutions obtained using a commercial solver.

Since the mid-1990s, roughly eight Chilean forest firms have been using PLANEX, which has reduced operational costs by 15–20 percent (Epstein et al. 2006). The two biggest enterprises in Chile, Bosques Aurauco and Forestal Celco, saved roughly US$20 million per year thanks to PLANEX and other operations research tools. Interestingly, nations in Central Europe that have traditionally relied on forestry as an industry have been slow to adopt such sophisticated systems, so ceding some of their operational margin and falling behind the competition.

The PLANEX system has been the most popular, although there are other options (Chung et al. 2004, Chung et al. 2008, Meignan et al. 2012). With PLANEX,

resulted in a 30% rise in both price and road length. These findings demonstrated the need for a site-specific approach to environmental effect mitigation and the lack of a universal "silver bullet" solution. Understanding trade-offs is essential for the expert-stakeholder conversation, which is enhanced by multi-objective optimisation methodologies. In another piece of research (Bont 2012), researchers looked at how to maximize the cost, protection from natural risks, and residual stand damage all at once in mountain protection forests. Cable roads and slope direction should be reduced to protect against natural hazards (snow creeping, flow avalanches), while uphill logging should be done to prevent residual stand damages. When compared to the cost-optimal option, the »slope-line-optimal« approach added 7% to the final price while eliminating cable roads down the slope.

By eliminating the effect of the slope line entirely, the »uphill-yarding-optimal« approach was shown to incur a 22% higher price. We found that our study was the first to semi-automatically produce a multi-goal har- vest/road-network design.

Discussion and Perspectives

The current evaluation aims to (1) highlight the concepts and methodologies for various road network planning strategies and (2) pinpoint breaks, at where significant advances were made. From rules-of-thumb ap- proaches in the 18th century to semi-automatic mathematical optimization approach- es at the turn of the 21st century, our analysis uncovered a variety of road network planning methodologies. Different techniques to layout are described in Table 1.

As a further step, quantitative techniques were used to better predict the appropriate road spacing, elevating the design approaches to a more scientific level (Table 1). Models of solely parallel and Manhattan grid layouts make it clear that road spacing is the only design feature that distinguishes the two. Mathematical identification of the optimum road spacing, a complementary attribute to optimal road density, has been the focus of a growing body of study that began with fundamental work in 1939 (Matthews 1939). On the other hand, ideal road spacing has been employed as a design criterion for the spatial layout of particular forest road networks, whereas optimal road density has been used primarily to create regulations for the amount of accessibility that should be reached on regional or national scales. methods exist to estimate the ideal road spacing, however the construction of road network layouts for certain terrain units has produced in a narrow collection of network options, from which the most acceptable alternative must be chosen. The primary network design criterion in all of the most popular textbooks on the subject of forest road network design, including (Dietz et al. 1984, Hafner 1971, Kuonen 1983, and Wenger 1984), was the manual arrangement of control points and road spacing.

In the 1970s, a new depiction of forest road network planning difficulties evolved, and with it came the emergence of the third kind of network design approach: op- timal entrance point access (Table 1). The new system identified harvesting units to be cut in various time periods, but the old one ignored the variability of the forest cover and the harvesting architecture. Logs were to be brought into each harvesting unit through a designated entrance point using non-motorized transport methods like skidding or a cable yarder. As soon as those doors are open were identified, a set of road segments was located, each connecting a pair of entry points. Experts had to do two tasks: locate the entry points and road seg- ments. The search for the minimum tree that connects all the entry points and the sequencing of road con- struction that considers harvesting activities taking place in different time periods was based on a math-ematical optimization formulation, which resulted in a near-optimal solution.

The U.S. Forest Service refined this approach, which became widely applied as the so-called Integrated Resource-Planning Model (IRPM) in the 1980s. The formal approach is nowadays known as the Multiple Target Access Problem (MTAP), for which there are exact solutions. This new, operations-research-based road network planning approach triggered a bifurcation in forest road network design methods. Whereas regions with considerable forestry tradition, such as Europe, stayed with traditional forest road network planning methods (control point and road spacing led expert layout), the North American forest road community moved to OR-based approaches, which started to be widely used, particularly by the U.S. Forest Service. Weintraub, Chilean, contributed to the development of OR-based road network design methods at an early stage of his career in the U.S., from where the methodologies spread to Chile.

The fourth type of road network design methods – CAE network optimization (Table 1) – appeared in the early 1990s in the U.S., triggered by the broad availability of digital elevation models (DEMs). It built upon the multiple target access problem, which required the planner to identify harvest units, their entry points and road segments between pairs of entry points manually. The representation of the terrain surface as a 3D-grid (see Fig. 4) made it possible to automate the layout of road segments between entry points, and the identification of harvesting units and the location of entry points were the only design task that a planner had to do. From a computational point of view, a shortest path algorithm has to be used to identify the set of the shortest path between all pairs of entry points, whereas minimal spanning tree algorithms provide optimal connection of the entry points to the exit points. The location of control points (entry points) has been the first step in road network design since the 1870s, and the computer-aided-engineering approach fully automated and optimized all the remaining design steps, resulting directly in an optimal solution.

Concurrent harvest/road network layout (Table 1) is the sixth category of road network design techniques that results from digital elevation model–based computer-aided engineering (DEM–CAE) network optimization.

The technique by simultaneously resolving the harvest/road network layout issue and the harvest layout. An international team of scientists from Chile and the United States, supported by the Chilean government, created PLANEX, a system that develops near-optimal harvest/road layouts for individual forest regions using a combination of automation and human input. The widespread adoption of PLANEX across eight major Chilean forest enterprises has led to substantial cost reductions for the sector as a whole. It was difficult to adapt this approach to regions with close-to-nature forestry projects since it was developed for clear-cutting regimes inside a plantation forestry setting. In an effort to improve the efficiency and accuracy of automatic road segmentation on a DEM, studies began appearing around 2005. These studies sought to adapt the problem formulation to close-to-nature and continuous cover silvicltural regimes and to find an exact solution to the problem for best results. Recent network design methods, on the other hand, have been mostly used in case studies. The high degree of road network growth and the paucity of abilities among road network professionals in the employment of quantitative, OR-based methodologies account for this restricted use.

Throughout the previous 150 years, significant scientific progress has been made in the design of forest road networks, as shown by the feature profiles presented in Table 1. First, between 1940 and 1960, the theory of optimum road spacing/density developed, offering for the first time a rational, data-driven approach to road network design. The second development, which emerged in the 1970s and 1980s and is now known as the Multiple Target Access Issue, modeled the road layout problem as a tim- ber flow problem from entrance nodes (harvest units) to exit nodes over a number of time periods (MTAP). While the planner was responsible for identifying and approximating the locations of entry/exit nodes and harvest volumes, the best potential connections between nodes were determined by a mathematical optimization software. The widespread availability of Digital Elevation Models (DEMs) prompted the third development, which established procedures for automatically identifying the minimum cost road path between any pair of entry points, thereby furnishing exhaustive data for determining the best possible minimum-cost connection between origin and destination. To depict harvesting units as a series of grid cells, from each of which logs have to »flow« on the shortest cost route to the exit nodes, the most recent development combined two spatial layout problems: road network design and harvest design. This most recent advancement brought together disparate fields including geospatial data, digital topography, and optimization mathematics.
things that need engineering and operations research
knowledge.

After examining how things have changed in the past, one could wonder whether the same tendencies would persist in the future. Given that OR-based road network layout techniques have historically only been used in clear-cut and plantation management regimes, the OR-based and the conventional forest road layout communities have been siloed. Traditional forest road layout communities continue to rely on forest publications while the road layout optimization community is actively exchanging information in the operations research journals. Education and training were also impacted by the split; many for- profit operations programs throughout the globe still place little emphasis on OR-based methodologies and instead emphasize more conventional road-spacing approaches. This necessitates the internationalization of forest road expert training programs, including but not limited to courses in road network planning. The second avenue for development is the expansion of all OR-based road network planning methods for multi-objective settings, which enables the identification of pareto frontiers that quantify extremely current trade-offs between efficiency (cost minimization) and environmental effect goals. Furthermore, finite element theory may lead to an enhanced representation of the terrain surface, which would be the third potential improvement. All of the aforementioned methods involve discretizing the landscape in a regular, lattice-like pattern. Triangular irregular networks (TIN) are a family of surface meshes that are superior than lattice-type mesh- es, and finite element theory gives a wide understanding of how to best represent the surface with a mesh (Lo, 2015). Their strength lies in the fact that places with considerable height variation have a finer granularity of basic components (triangles) than those with low variation. Transitioning away from lattice

Updating from DEM-type data to TINs or even more complex mesh- es (Lo, 2015) would further enhance the quality of the solutions. A fourth avenue for development is the combination of road network design and thorough road engineering. As part of the process of designing a road system, corridors are determined to be suitable for the eventual placement of the roadway's centerline. New possibilities have opened up with the release of Digital Elevation Models (DEMs) created using data collected by aerial light detection and ranging (LIDAR) devices. The price of creating high-resolution digital elevation models has dropped dramatically due to the advent of unmanned aerial vehicles (UAVs) and low-mass LIDAR sensors with weights of less than 5 kg (Favorskaya and Jain 2017). A promising future

In this scenario, a UAV-borne LI- DAR sensor would scan all road corridors based on an ideal or near-optimal road network configuration, yielding a geo-referenced point cloud from which a high-resolution DEM could be produced. In road engineering, the first step is to determine where the traverse will go so that the junction locations can be established, and then the vertical alignment can be determined. Until recently, both of these tasks required human intervention; only within the last decade or so have academics developed a semi-automatic technique that can optimize horizontal and vertical alignments simultaneously to save building and maintenance costs (Aruga 2005). In order to cut down on construction, maintenance, and transportation costs, engineers are working to integrate road networks and precise road engineering. A fifth direction for development is the enhancement of optimization methods. One of the most advanced systems, PLANEX, is still based on a heuristic solution technique that only produces near-optimal results rather than perfect ones. It is expected that the trend of computers and optimizers becoming more powerful to solve big mixed-integer problems to optimality will continue. It is important not to overlook the fact that intelligent model formulation and the tuning of integer programming algorithms may significantly cut down on solving time and make problems tractable, leading to practical or near-optimal solutions (Klotz and Newman 2013). Set cover problem formulations provide hope for reducing the scope of the issue and finding optimum or nearly perfect solutions (Bont et al. 2015). Last but not least, it is not entirely clear how the scientific breakthroughs from the early transport geometry approaches (Launhardt 1872, Schuberg 1873) spread and evolved into the traditional layout theory, as represented by traditional text- books (Dietz et al. 1984, Hafner 1971, Kuonen 1983, etc.).

A. Wenger, 1984).

References

Abegg, B., 1978: Die Schaetzung der optimalen Dichte von Waldstrassen in traktorbefahrbarem Gelaende. Mitteilungen, Eidgenoessische Anstalt fuer das forstliche Versuchswesen 52(2): 99–213.

Aruga, K., 2005: Tabu search optimization of horizontal and vertical alignments of forest roads. Journal of forest research 10(4): 275–284.

Ashe, W.W., 1916: Cost of Logging Large and Small Timber. Forestry Quarterly 14(3): 441–452.

Backmund, V.F., 1966: Kennzahlen für den Grad der Erschließung von Forstbetrieben durch autofahrbare Wege. Forstwissenschaftliches Centralblatt 85(11): 342–354.

Belhoste, B. 1989. Les Origines de l'École polytechnique. From the Central School of Public Works to the Academy of Engineering. 42(1), Histoire of Education, pages 13–53.

Spatially explicit optimization of forest harvest and transportation system architecture under steep slope circumstances. Bont, L., 2012. ETH. Last accessed on [Dec.28, 2016] through [http://dx.doi.org/10.3929/ethz-a-007558027].

Concur- rent optimization of harvesting and road network architectures in mountainous regions. Bont, L.G., Heinimann, H.R., and Church, R.L., 2015. Journal of the Operational Research Society 232(1):41-64.

E.A. Braniff's 1912 book. Management Theory and Practice in the Lumber Industry Potential Career Path for Those Interested in Forestry. The Forestry Quarterly 2010;10(1):9-14.

Shifting the Classical Road and Landing Spacing Model and Its Effects, Bryer, J.B., 1983. Number 29 of Forest Science is "670-674."

"Skyline logging profiles from a computerized ter- rain model," by David Burke in 1974. Skyline Logging Symposium, University of Washington, Seattle, Washington, 1974, pp. 52-55.

An application of a heuristic network method to cable logging arrangement design. Chung, W., Sessions, J., and Heinimann, H.R., 2004. The first fifteen issues of this international magazine on forest engineering ran from 2011 to 2014.

Forest road network design employing a trade-off analysis between skidding and road building costs. Chung, W., Stückelberger, J., Aruga, K., Cundy, T.W. 2008. For the full citation, please use: Canadian Journal of Forestry Research 38, no. 3 (pp.

Locational concerns in forest management. Church, R.L., A.T. Murray, and A. Weintraub. 1998. Geographical Research Letters 6(1-4): 137–53.

P. Cossens and colleagues 1992 Short-term log allocation planning and management in New Zealand. In the book titled "Integrated Decision-Making in Planning and Control of Forest Operations," Connecticut: Yale University Press, p.

Walderschliessung: A Textbook for Academic and Practical Use, with Special Consideration Given to Wood Path Construction Dietz, Peter Knigge, and Hans-Peter Löffler. 1984. ...Hamburg, etc. A total of 426 pages can be found in Parey.

Duhamel H.-L. du Monceau and B.-L. prévost, 1767: Du transport, de la conservation et de la force des bois, où l'on trouvera des moyens d'attendrir les bois, de leur donner diverses courbures, particulièrement pour la construction des vaisseaux; et de former des pieces d'assemblage pour sup- plé- plé- rir en l'absence des pieces simples faisant la conclusion du Traité complet des bois et des forets. Paris. Delatour, L.F., 556: XXVII p.

An application of facilities placement theory to the planning of forest harvesting zones, Dykstra, D.P., and Riggs, J.L., 1977. Articles in the Journal of the American Institute of Industrial Engineers 9(3), pp. 270-277.

Use of OR systems in Chilean forest industry. Epstein, R., Morales, R., Seron, J., & Weintraub, A. (1999). Interfaces, 29(1), pp. 7-29.

R. Epstein, M. Rönnqvist, and A. Weintraub. 2007. Forest transportation. Natural resources operations research handbook. Page numbers range from 391 to 403 and are published by Springer.

Epstein, R.; Weintraub, A.; Sapunar, P.; Nieto, E.; Sessions, J.B. ; Sessions, J.; Bustamante, F.; Musante, H.; 2006: A combinatorial heuristic method to tackling large-scale forestry machine placement and road design challenges. The pages 1017-1027 of the 54th issue of Operations Research.

2001: PLAN- EX: A system to identify landing spots and access. Epstein R., Weintraub A., Sessions J., Sessions B., Sapu- nar P., Nieto E., Bustamante F., Musante H. Proceedings of the 11th Pacific Northwest Skyline Symposium and the International Mountain Logging Symposium, edited by. Seattle: Schiess, P., and F. Krogstad. 190-193 pages, University of Washington, College of Forest Resources.

An Overview of LiDAR Technologies and Equipment for Mapping Land Cover Favorskaya, M.N., Jain, L.C., 2017. Remote sensing and geographic information systems: a handbook of recent advances Edited by: Favorskaya, Maria N., and Jain, L.C. Pp. 19–68. Springer International Publishing.

It was first published in 1962 by Ford and Fulkerson. A town in New Jersey called Princeton. This hefty tome from Princeton University Press has 194 pages.

A.J. Gayson, 1958: Road Density in Extraction Planning. 37(3), 305-310. Empire Forestry Review.

Transportation networks in forest harvesting: conceptual foundations. Greulich, F., 2002. Yoshimura, T. (editor), Tokyo: International Symposium on the New Roles of Plantation Forestry Calling for Appropriate Tending and Harvesting Operations. Published by the Japanese Society of Forest Engineers, pages range from 57 to 65.

Forest Road and Path Construction by F. Hafner, Vienna, 1956. 399 pages, Fromme.

Adapted from Hafner, F. 1971. Forstlicher Strassen- and Wegebau. 2., freshly edited edition. This edition was written by Wien. Publisher: Oesterreichischer Agrarver- lag. 360 pages.

To distinguish between skidder and cable-yarder based road network designs on steep slopes, Heinimann (1998) developed a computer model. This study was published in Volume 3 Issue 1 of the Journal of Forestry Research.

Handbuch für dem Holztransport und das Flosswesen zur Gebrauche für Forstmänner and Holzhändler, und für jene, die es werden wollen. Jägerschmid, K.F.V., 1827. The first volume covers lumber harvesting, layout, and transport to the mainland. Verlag der Ch. Fr. Müller'schen Hofbuchhandlung, Karlsruhe, 391 p.

It was first published in 1966 by Kanzaki (K.) as A design of the forest road network using graph theory. 48(10): 365-371 in the Journal of the Japanese Forestry Society.

M. Kirby, 1972: Planning and Decision-Making in the Context of Forest Harvesting: A Resource-Allocation Procedure Corvallis, Oregon: J. O'leary, J., School of Forestry, Oregon State University, pp. 75-83.

M. Kirby, 1986, "Simultaneous Planning of Wildland Management and Transportation Options," in Journal of Environmental Planning and Management. Management Studies, Vol. 21: pp. 371-387.

Optimization of Rural Road Networks - An Application of the Timber Transshipment Model. Kirby, M., P. Wong, and W. Cox. 1979. A Collection of Edited Essays about the Back Roads of Rural America. Agricultural Research Service, U.S. Department of Agriculture, and the Bunker, A.R., and T.Q. 17–26 pages of economics, statistics, and the cooperative service.

Guidelines for solving challenging mixed-integer linear programs: a practical approach. Klotz, E., and Newman, A.M., 2013. Studies in Operations Research and Management Science, 18(1), 18-32 .

Planning method for road-route locations in high woods. Kobayashi, H., 1984. The 66th issue of the Journal of the Japanese Industrial Society has articles on pages 313 and 319.

On the smallest spanning subtree of a graph and the traveling salesman problem, by J.B. Kruskal (1956). American Mathematical Society Proceedings 7.1 (January 1902): 48–50.

Planning, Prototyping, and Building Pfaffhausen's Forest and Commercial Streets by V. Kuonen (Eigenverlag, Pfaffhausen, 1983).

The use of computerized terrain models to solve the highway placement issue. Laflamme, R.A., 1959. Civil and Sanitary Engineering Department, Massachusetts Institute of Technology (MSc).

Lalanne, L. 1863. Essai d'une théorie des réseaux de che-mins de fer, based on empirical data and the fundamental laws that govern population clustering. The proceedings of the Academy of Sciences 57(2):210.

Studies on Forest Road Planning, by G. Larsson (1959). 147: Kungl. Tekniska Hoegskolans Handlingar (Transactions of the Royal Institute of Technology), pp. 1–136.

Commercial Tracing of Transportation Routes. Launhardt, W., 1872. There are a total of 32 pages in this Hannover publication.

A tabu search technique to resolving a challenging forest harvesting machine location issue. Legües, A.D., J.A. Ferland, C.C. Ribeiro, J.R. Vera, and A. Wein- traub. 2007. 179(3), pages 788–805 of the European Journal of Operational Research.

Preliminary design of road systems utilizing computerized terrain models. Liu, K., & Sessions, J. (1993). Engineered Forestry, 4(2), 27-32.

C.I. Mandt, 1972, Network Analysis in Transportation Planning. O'leary, J. (editor), Corvallis, Oregon: Planning and Decisionmaking for Forest Harvesting. Oregon State University, School of Business, pp. 95-102.

Estimating Logging Expenses and Making Logging Plans, by David M. Matthews (1939). Forestry Journal 37(10):783-787.

Cost Management in the Forest Products Industry, by D.M. Matthews (1942). Forestry in the United States: The Big Apple: New York. McGraw-Hill, 374 pages.

A heuristic approach to automated forest road location. Meignan, D., Frayret, J.-M., Pesant, G., Blouin, M., 2012. Published in the Canadian Journal of Forest Research, 42(12), pp. 2130-2141.

The concept and use of the digital terrain model. Miller, C.L., 1958. 107 pages, Master of Science in Civil and Sanitary Engineering from MIT.

Access route design for harvest sites. Murray, A.T., 1998. The Canadian Journal of Forestry Research 28(7): 1084-1087.

Planning and Decisionmaking in Forest Harvesting. O'leary, J., 1972. In 160. It's in Corvallis, Oregon. Oregon State University's School of Forestry.

French road network planning theory (Picon, A., 2016). Email conversation with the author, 21 July 2016.

Shortest connection networks, and some generalizations. Prim, R.C., 1957. Technical Journal of the Bell System 36(6):1389-1401.

Improved Steiner tree approximation in graphs. Robins, G., & Zelikovsky, A., 2000. To be published in the proceedings of the eleventh annual ACM/SIAM conference on discrete algorithms. In the proceedings of the SIAM (Society for Industrial and Applied Mathematics), pages 770–779.

K. Schuberg published Der Waldwegbau and its Preliminaries in 1873. The second album in the series. Construction procedures, cost overruns, and building construction in profitable businesses. Berlin. 575 pages by Julius Springer.

Distances Traveled Across Countries for Transportation and the Growth of the Road Network, Segebaden, G.V., 1964. Studies in Swedish forest ecology, volume 14.

Sessions, J. 1987. A heuristic approach for the solution of the transportation issue with both variable and fixed costs. published in System Analysis in Forest Resources: Proceedings of the 1985 Symposium. Institution of higher learning located in Athens, Georgia. Georgia State University, pp. 324–336.

"Silversides, C.R., 1963: How different logging techniques impact the layout of a transportation network's technological infrastructure. Genève, Switzerland: Proceedings of the Symposium on the Planning of Forest Communication Networks (Highways and Cables). pp. 299-308 in Joint Committee on Forest Working Techniques and Training of Forest Workers.

Report of the Research Briefing Panel on Decision Making and Problem Solving Simon HA, Dantzig GB, Hogarth R, Plott CR, Raiffa H, Schelling TC, Shepsle KA, Thaler R, Tversky A, Winter S. 1986. Research Briefings, E. Committee on Science and Public Policy (Editor), National Academy Press (Washington, DC), pp. 17–36.

To retrace one's steps and measure one's progress; Soom, E., 1950. This article may be found in volume 100 of the Swiss Forestry Review.

SOOM, E. 1952. Inertia and pathos in the rukken of firewood. Swiss Journal of Economics and Statistics, Volume 102 (8).

H. Stoetzer published Waldwegebaukunde: A Practical Guide to Trail Construction in 1877. The "Main" city of Frankfurt, Germany. J.D. Sauerländer's, Verlag Sauerländer's, 170 pp.

Waldwegebaukunde nebst Darstellung der wichtigsten sonstigen Holztransportanla- gen ein Handbuch for Practiker and Leitfaden for the Un- terricht, 5., bearb. von Hans Hausrath Ed. Frankfurt am Main: A., Sauerländer, M.J.D., 1913; 251 p.

Piecelberger, J.; Heinimann, H.R.; Chung, W.; 2007: Improved road network design models taking into account

Includes a wide range of possible road layouts and connecting structures. Can. J. For. Res., 37(11), pp. 2281-2298.

Modeling regional heterogeneity in life-cycle costs of low-volume forest roads. Stückelberger, J.A., H.R. Heinimann, and E.C. Burlet. 2006. The European Journal of Forest Research 125(4): 377-390.

Automatic road-network design for numerous objectives. Stückelberger JA, Heinimann HR, Chung W, Ulber M., 2006b. At the 29th Annual Forest Engineering Conference. Employing a Worldwide Approach - Forest Engineering: Global Perspectives and Local Solutions, edited by Chung, W., Coeur d'Alene. Page numbers range from 233 to 248 and are courtesy of the University of Montana.

Average skidding distance for theoretical study of logging expenses. Suddarth, S.K., and A.M. Herrick. 1964. 52 pages long. USDA Forest Service Bulletin (789).

Studies on the Transport System of the Swedish Forest Industry. Sundberg, U. Swedish Forestry Society Journal (Svenska Skogsvrdsföreningens Tidskrift) 51(1):15-72.

Economic Road Standard, Road Spacing, and Related Questions, Sundberg, U., 1963. Some Thoughts on the Conceptualization of a Non-Alpine Forest Road System Genève, Switzerland: Proceedings of the Symposium on the Planning of Forest Communication Networks (Highways and Cables). Techniques for Working Forests and the Education and Training of Forest Employees, a Joint Committee Report, pp. 231–247.

Taylor, F.W. (1895): A piece-rate system: Toward a partial solution to the labor issue. ASME 16(647):865-903 in the journal Transactions.

Overhead costs in road and landing spacing models. Thompson, M.A., 1992. Forest Engineering, Volume 3 Number 2 (2013): 13-19.

Der isolating state in relation to land wealth and national economy / or studies of the effect of commodity prices, soil fertility, and taxation on agricultural output / by J.H. Thünen (1842). In Rostock, G.B., at Leopold's Universitäts-Buchhandlung, 3 Theile.

Authors Twito, R.H., S.E. Reutebuch, R.J. Mcgaughey, and C.N. Mann published an overview of the PLANS system in 1987. Portland, Oregon Technical Report by the USDA Forest Service.

A lagrangian relaxation technique for an equipment location issue in forest harvesting. Vera, J.R., Weintraub, A., Koenig, M., Bravo, G., Guignard, M., and Barahona, F., 2003. Operational Research 23(1):111-128.

INCOSE Systems Engineering Handbook: A Guide for System Life Cycle Processes and Activities, 4ed. Hoboken: Walden, D.D., Roedler, G., Forsberg, K., Hamelin, R., Shortell, T., 2015. In 290 pages, Wiley.

A planning model for forest management that incorporates forestry and transportation Weintraub, A., and D. Navon, 1976. The journal Management Science published its 22nd issue on pages 1299-1309.

Weisstein, E.W., online-a: Greedy Algorithm. In Wolfram Web Ressources. To be had on [Dec-28-2016]. Click to [http://mathworld.wolfram.com/GreedyAlgorithm] to learn more about a greedy algorithm .html]

To cite this article: Weisstein, E.W. "online-b: Minimum Spanning Tree," in Wolf- ram Web Ressources. Get it at [Dec-28-2016]. See also: [http://mathworld.wolfram.com/MinimumSpanningTree.html].

The Steiner Family Tree. Weisstein, E.W., online-c. To be found at Wolfram Web Resources. Get it at [Dec-28-2016]. See also: [http://mathworld.wolfram.com/SteinerTree.html].

Wenger, K.F. (1984) The Forestry Handbook, Second Edition. New York. Wiley, 1335 pages.