Forest Road Network and Transportation Engineering – State and Perspectives

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Abstract

The paper reviews traditional and computer-assisted road network layout approaches and brings them together in an overall stream of development. It results in the main finding that changes in the representation of the road network layout problem triggered major scientific advancements. A systematic, 2D transport geometry representation emerged in the 1870s and led to the mathematical derivation of optimal road spacing. The representation of road network and harvest layout problem as a mathematical graph and the solution of the corresponding linear programming problem, triggered a representational shift in the early 1970s. The broad availability of digital elevation models DEMs at the beginning of the 1990s was another representational innovation, enabling an automatic road route layout on the terrain DEM surface. The most recent shift consisted of systems to semi-automatically, concurrently laying out harvest/transport-network problems on DEMs in the mid-1990s. The review identifies challenges for future research, among which the extension of the concurrent harvest/road-network layout systems for multi-objective functions is the first importance. Considering that scientific advancement is mostly going along with changes in problem representations, research should explore improved representations for lattice type terrain representation, among which triangular irregular network (TIN) meshes seem to be the first interest. Additional paths for improvements are the integration of road network planning with detailed road engineering, the refinement of optimization problems formulations, and the cross-national adaptation of road network planning courses to operations-research-based approaches.

Keywords: road network, network layout, road spacing, road density, computer-assisted network layout

1. Introduction

An efficient road network has been the backbone of forestry, the design of which is based on fundamental principles. Those principles have been changing in time due to scientific advancements and due to the evolution in both off-road and on-road transportation technology. The underlying scientific concepts cover a broad range. Computer-assisted systems that are automatically generating the concurrent layout of road and harvesting systems represent the edge of development (Epstein et al. 2006, Epstein et al. 2001), with a scope on plantation forestry conditions. On the other hand, traditional expert approaches, which are relying on the skills and experience of the designers, are still in use and are still part of training programs for forest operations specialists. Although, according to Google Scholar, there have been about 70 scientific publications on forest road network planning since 1960, there is no comprehensive review of the state of knowledge in the field. Traditional text and handbooks (Dietz et al. 1984, Hafner 1971, Kuonen 1983, Wenger 1984) documented expert-based approaches, while review articles (Church et al. 1998, Epstein et al. 2007) summarized the state of knowledge for mathematical approaches stemming on operations research techniques.

The goal of the present contribution is to bring computer-assisted and traditional road network layout approaches together and to sketch an overall stream of development. In particular, it aims to:

⇒ bring out the concepts and methods for the different conceptual approaches in time

⇒ identify discontinuities, at which major progress occurred.

The following reflections will focus on forest road networks, thus neglecting other types of low-volume road networks. Additionally, they will cover the time span from the emergence of scientific literature on forest road networks by the end of the 18th century until today. The article will first sketch the early developments up to World War I, and second, analyse the transport geometry approach that led to the concept of optimal road spacing. Third, it will review approaches that were using operations research tools that developed further into semi-automatic computer-aided road network layout methods. Finally, we will discuss computer-aided approaches to concurrently layout road network and harvesting systems.

2. Early Developments

The establishment of the French state Corps of Bridges and Roads (Corps des Ingénieurs des Ponts et Chaussées) in 1716 was the nucleus for enlightened, modern engineering sciences (Belhoste 1989). Before, engineering knowledge was tacit without formal knowledge generation and dissemination, and without formal education and training systems. Modern engineering sciences grew out of a military initiative, the foundation of the Corps of Fortifications (Corps des Ingénieurs des Fortifications) in 1691. French military ambitions – the establishment of a powerful fleet and the construction of fortifications – required an improved timber supply system. A French marine engineer, Duhamel du Monceau, was a mastermind of the wood supply improvement programme, which he documented in a series of books, among which »Transport, Conservation and Forces of Timber« (Duhamel Du Monceau and Prévost 1767) documented forest transport practices of those times. Waterborne transport with vessels or by rafting was the backbone of transportation, in particular for long distances. Land transportation was mainly limited to charcoal and firewood to the nearest centres of usage (villages, cities), and large -sized »carpenter timber« could not be transported with carriages or carts, because their carrying capacity was limited to about two metric tons. Although France was the cradle of engineering sciences, there was no theory on land transportation until the 1860s (Picon 2016). About 60 years after Duhamel's book, a German textbook »Handbook on Timber Transport and Floating« appeared (Jägerschmid 1827), describing the transportation practices at that time. There were two road standards, one for firewood and one for roundwood. The author did not give technical specifications for the layout of road networks, but for vertical alignment and cross-section design, which are essential for detailed road engineering. Since biomechanical power (humans, draught animals) was the only energy source for locomotion, gradients had to be limited to about 8%. Both Duhamel and Jägerschmid, took a purely technical point of view, thus totally neglecting economic aspects, which can be explained by the fact that mercantilism was the dominating economic paradigm that was only slowly replaced by classical economics.

In 1842, von Thünen wrote a seminal book »The Isolated State about Agriculture and Political Economy …« (Thünen 1842), which is somewhat the cradle of location theory and transportation economics. Thünen investigated how different types of land uses arranged spatially around a city that had absolutely no economic exchange with other economic entities. For that kind of assumptions, various types of land-uses arrange in concentric rings. He investigated where the production of timber should be located, concluding that this would happen in a second circle. The outer limit was at about 8 miles, beyond which the transportation was economically infeasible because transportation cost became higher than timber prizes. One horse and carriage unit was able to transport about two m³ of firewood and could do a distance of about 20 to 30 km a day, which illustrates how demanding land transportation was at that time.

Around 1840, a discontinuity in the development of transportation technology occurred with the appearance of large-scale railway networks. This development cut ground transportation costs tremendously, triggering the exchange of goods over long distances. Around 1860 the theory of transport network layout emerged concurrently in Germany and France (Lalanne 1863, Launhardt 1872), providing quantitative methods for the design of transport networks. Both authors introduced a conceptual design phase – nowadays called »architecture definition process« (Walden et al. 2015), aiming to find the best possible topological network arrangement. Urban transportation started with the centres of traffic demand and then looked for the best possible connection. Whereas the French approach was purely geometric, Launhardt's approach was quantitative. His conceptual design phase, which he called »commercial trace« (Launhardt 1872), totally neglected terrain conditions, aiming to layout the best possible network on a two-dimensional plane. His process started with the identification of »transport locations« (cities, villages, production plants) and their specific traffic inflows and outflows. The problem was then to find a network that connects all the transport locations at minimal transportation cost. He developed a procedure to optimally locate intersection points, considering the traffic flow and the geometry of the adjacent points. Overall, Launhardt's method resulted in a type of Steiner tree, connecting all the »transport locations« to the network. The succeeding detailed road route engineering phase – now called »design definition process« (Walden et al. 2015), which Launhardt called the »technical trace«, aims to locate road routes on the terrain and to define the vertical alignment of the road centreline in such a way that it considers the technical constraints and results in a smooth horizontal and vertical alignment. It is not clear how this seminal work affected the theory of forest road network planning. However, some key conceptual design ideas, such as the definition of »transport locations« (»fixed points«, »control points«) and the search for a network topology can still be found in later textbooks (Dietz et al. 1984, Hafner 1956, Kuonen 1983, Wenger 1984).

The book »Forest Road Construction and Its Preliminary Work« (Schuberg 1873) is, to our knowledge, the first textbook with a comprehensive treatment of forest road networks. The author recognized that transportation planning in forestry is not a point connection problem, but a problem of how to make a whole area accessible as even as possible. Schuberg introduced principles of forest transport geometry, quantifying the relationship between road spacing and average skidding distance ASD, although his analytical solutions might not be correct, yielding an ASD of 5/24 road spacing, which is however quite close to the correct solution of 1/4 road spacing. He suggested lattice-type road networks for gentle terrain with an average road spacing of up to 700 m, if there is a secondary network of skidding roads. In hilly terrain, the terrain constraints the route location, resulting in network types that were called »contour-type networks«. Following Launhardt's logic, those considerations defined the conceptual layout of forestry road networks. The detailed road network layout had to stem on reliable contour maps, and compass-based methods to layout routes with a regular grade by stepping with a constant distance from one contour to the next were already known. Once a good enough solution was found on the map, the design was transferred to route locations in the terrain with the use of surveying instruments. It is not clear how Schuberg's methods spread because other textbooks were focusing on road engineering and road construction (Stoetzer 1877, Stoetzer and Hausrath 1913). In North America, road network and transportation engineering started to become formalized around World War I (Greulich 2002), amplified by the need for economic rationalization and the understanding of logging cost. World War I triggered another discontinuity in development with a boost of motor-vehicle-based transport systems after the 1920s, which resulted in quantitative insights that will be discuss below.

3. Optimum Road Spacing/Optimum Road Density

The emergence of industrial engineering as a scientific discipline in the aftermath of Taylor's seminal work on time studies (Taylor 1895) resulted in an improved understanding of production cost and productivity. It had a stimulating effect on scientific studies in forest operations (Ashe 1916, Braniff 1912), leading to an increasing number of time and cost studies. By the end of the 1930s, the tractor started to appear for skidding operations, enhancing the alternatives to design forest harvesting systems tremendously. An operational study reflected this new variability (Matthews 1939), coming to a conclusion that – depending on road conditions – off-road transportation cost per unit of volume and unit of transportation distance were about 6 to 9 times higher than on-road cost. The figures led to the insight that increasing the share of on-road transportation, while decreasing the proportion of off-road transportation, must lower the total cost up to a minimum, beyond which the total cost would raise again. In his seminal paper (Matthews 1939), Matthews raised the question at what road spacing this minimum would occur. He developed a transport geometry model that was based on the following assumptions:

- ⇒ terrain conditions of the forest area are flat, homogeneous, and consequently, road building cost are constant, while off-road transportation costs depend only on the distance
- ⇒ road network layout follows a pattern of parallel roads with equal road spacing, and there are no links between those routes
- ⇒ road network is built at one point in time; there is no sequencing across several time periods
- ⇒ Off-road transportation takes place on the shortest path between the loading point in the stand and the landing point on the road
- ⇒ forest stand conditions are homogeneous for the whole area
- ⇒ there is one forest management strategy that applies to any part of the area under consideration.

Matthews' mathematical formulation (Matthews 1939) is not straightforward, and some relationships, such as between road length and road spacing for a unit area, appeared implicitly in his formulation. This is why a more comprehensible formulation follows below. Fig. 1 illustrates the basic transport geometry model, characterized by road spacing (s_r) and road length (L). Assuming that the area covered by s_r and L equals the unit area A_u, road spacing s_r equals the unit

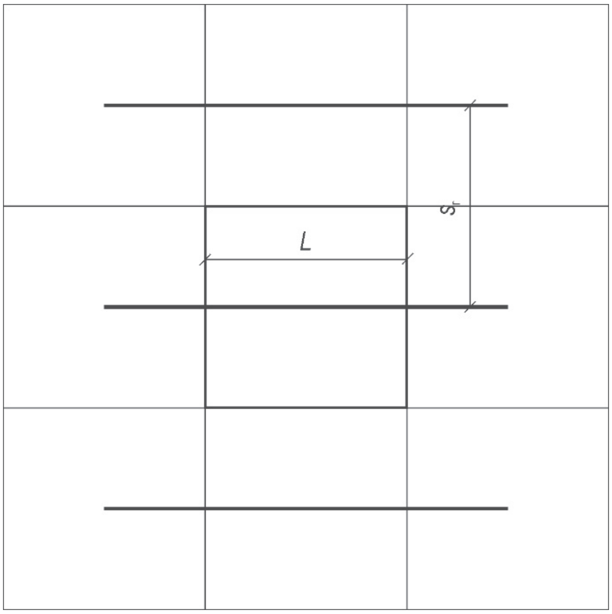

Fig. 1 Transport geometry for a system of parallel roads. L = lengths of road segment, s_r = road spacing

area A_u divided by the length L of the road segment (1). Equation [1] makes it possible to express both s_r and L, respectively, as a function of s_r.

$$\text{From } L \quad s_r = A_u \text{ it follows } s_r = \frac{A_u}{L} \tag{1}$$

Where:

L length of road segment, m

s_r road spacing, m

A_u unit area, m^2

A_u equals 1 (length-unit)^2 if length and area units are consistent. It has been a tradition, in particular in Europe, to use non-consistent units, meters for length and hectares for the area. If A_u is expressed in hectares (2), unit consistency can be achieved by multiplying with a conversion factor (10,000 m^2 per hectare), which results in (2).

$$L \times s_r = A_u \left(ha \times \frac{10{,}000 \times m^2}{ha} \right) \tag{2}$$

Where:

L length of road segment, m

s_r road spacing, m

A_u unit area, ha

Solving (2) for road spacing s_r yields (3), expressing road spacing in meters:

$$s_r = \frac{10{,}000 \times A_u}{L} \left(\frac{ha}{m} \times \frac{10{,}000 \times m^2}{ha} \right) \tag{3}$$

Below, any formula will be based on consistent length and area dimensions. Matthew represented the cost of road construction per unit of volume as (4):

$$C_r = \frac{c_r}{s_r \quad V} \tag{4}$$

Where:

C_r road cost, EUR·m^{-3}

c_r road construction cost, EUR·m^{-1}

s_r road spacing, m

V harvesting volume, m^3·m^{-2}

Writing the skidding cost per unit of volume results in (5):

$$C_s = \frac{s_r \quad c_s}{4} \tag{5}$$

Where:

C_s skidding cost, EUR·m^{-3}

c_s variable skidding cost, EUR·m^{-1}·m^{-3}

s_r road spacing, m

Summing (4) and (5) up yields (6):

$$C_{tot} = C_r + C_s = \frac{s_r \quad c_s}{4} + \frac{c_r}{s_r \quad V} \tag{6}$$

The derivative of (6) with respect to s_r yields (7), which is a quadratic equation:

$$C'_{tot} = \frac{c_s}{4} - \frac{c_r}{s_r^2 \times V} \tag{7}$$

Finally, setting $C'_{tot} = 0$ and solving (7) for s_r yields the Matthews formula (8), which explains the optimal road spacing with three variables: skidding cost c_s, road construction cost c_r, and harvesting volume V.

$$s_{r,opt} = \sqrt{\frac{c_r \quad 4}{c_s \quad V}} \tag{8}$$

Since Matthew used imperial units, acres and feet, his mathematical constant in (8) equals 0.33 instead of 4. Matthew did not use calculus to derive (8); he made use of the fact that total cost becomes minimal if road cost C_r and skidding cost C_s are equal. He used different data sets that were characteristic for the southern US to calculate optimal road spacing, arriving at spacing ranges between 1700 and 3800 feet, which equals 520 m and 1160 m, respectively.

Whereas road spacing is a network design parameter, road density is a »dual« parameter that equals the inverse of road spacing. Road density is the ratio between the length L of the road segment and the unit area A_u (Fig. 1, (9)).

$$RD = \frac{L}{A_u} \tag{9}$$

Multiplying road density (9) with road spacing (1) yields the primary relationship (10), yielding that road spacing s_r is the inverse of road density RD and vice versa.

$$RD \quad s_r = \frac{L}{A_u} \quad \frac{A_u}{L} = 1 \tag{10}$$

Replacing s_r with $1/RD$ and solving it for RD, yields the equation for the optimal road density (11), which is the inverse of (8).

$$RD_{opt} = \sqrt{\frac{c_s}{c_r} \quad \frac{V}{4}} \tag{11}$$

Different countries developed different traditions. Whereas the road spacing point of view has been dominating in the US, the road density view has been dominating in Europe. As equations (8) and (11) demonstrate, there is a duality between the two viewpoints, and the implications for road network layout planning are the same.

A Swiss investigation derived a mathematical approach to identify the optimal road spacing (Soom 1950, 1952) for both industrial timber and fire wood extraction. Although the author seemed not to have been aware of Matthews' work, the basic formalism is the same. He relaxed the assumption that extraction costs are strictly linear to the extraction distance by introducing a quadratic extraction cost function. The analysis resulted in optimal road spacing of about 500 m, which was significantly larger than the then customary best practices.

More or less at the same time, Ulf Sundberg started his work on transportation economics at the Department of Operational Efficiency at the Royal College of Forestry in Sweden. In a study (Sundberg 1953), he 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) with those correction factors to derive the optimal road spacing. His work triggered some follow-up studies, such as a study to identify the optimal road standard and the spacing of roads on networks with primary and secondary roads (Larsson 1959). Another study (Segebaden 1964) investigated how the assumptions of purely parallel roads and the shortest off-road transportation path could be relaxed and introduced into the determination of the optimal road spacing and the optimal road density, respectively.

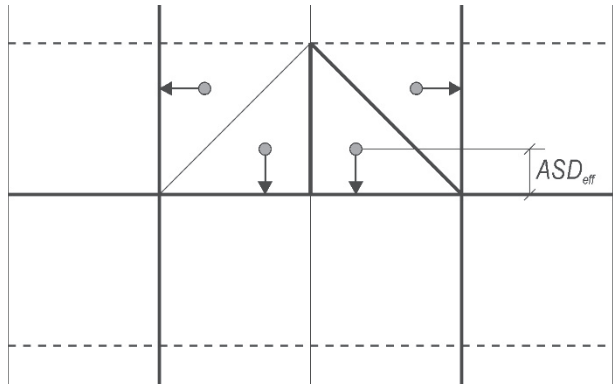

Fig. 2 Transport geometry for a lattice-type road network, s_r = road spacing, ASD_{eff} = effective yarding distance

Fig. 2 illustrates the relaxed transport geometry for a lattice-type road network. Assuming that there are two systems of parallel roads, being perpendicular to each other, a comparison with the basic model of Fig. 1 yields that the road network layout affects the average skidding distance ASD, which goes into the skidding cost function (5) as the road spacing s_r divided by 4.

Considering that road spacing and road density are reciprocal, the average skidding distance equals the reciprocal of 4 times the road density (12). The unit area in Fig. 2 equals $4s_r^2$, while the road lines per unit area are $4s_r$. Introducing those terms into (12) yields the average skidding distance, $s_r/4$, which we call theoretical average skidding distance because ASD_{theor} is predicted by the basic model.

$$ASD_{theor} = \frac{1}{4 \quad RD_1} = \frac{4 \quad s_r^2}{4 \quad 4 \quad s_r} = \frac{s_r}{4} \tag{12}$$

Fig. 2 illustrates how the extraction pattern looks like for a lattice-type network. Assuming that logs are moving on the shortest path to the nearest road results in a pattern of 8 triangles per unit area, and the average skidding distance for a single triangle equals the distance from its centroid to the nearest road, which is one third of the road spacing s_r (13).

$$ASD_{eff} = \frac{s_r}{3} \tag{13}$$

If we calculate the ratio between the effective and theoretical average skidding distance (14), we get a factor of 1.33, which is characteristic for triangular, rectangular, and hexagonal networks (Segebaden 1964). Matern, a mathematician, analysed a Poisson field type network for Segebaden, demonstrating that the corresponding network correction factor c_{net} equals exactly 2.0.

$$c_{net} = \frac{ASD_{eff}}{ASD_{theor}} = \frac{s_r \quad 4}{s_r \quad 3} = 1\frac{1}{3} \tag{14}$$

If we take the inverse of the network correction factor c_{net}, we get a metric for the road network layout efficiency e_{net}, which was introduced based on empirical investigations (Backmund 1966).

$$e_{net} = \frac{ASD_{theor}}{ASD_{eff}} = \frac{s_r \quad 3}{s_r \quad 4} = \frac{3}{4} \tag{15}$$

Segebaden introduced the network correction factor c_{net} into the skidding cost term of the total cost function (6). Additionally, he proposed an off-road transport correction factor c_{offr} that considers that logs do not move on the shortest path to the nearest road. Considering both, c_{net} and c_{offr}, the overall cost function results in a generalized cost function (16).

$$c_{tot} = \frac{s_r \quad c_s \quad c_{net} \quad c_{offr}}{4} + \frac{c_r}{s_r \quad V} \tag{16}$$

Road network developments are long-term investments, which require a capital budgeting view, balancing cost and revenue flow over the whole project lifecycle. The formula for optimal road spacing (8) and road density (11), respectively, do not consider this long-term investment aspect. The equivalent annual cost (EAC) approach is a straightforward method to calculate the cost of owning and operating an asset over its entire lifespan. Assuming that the road network has a lifespan of 50 years and that a conservative value for the interest rate is 2%, an annuity factor of 3.18% is obtained. If the interest that has to be paid for the capital is neglected, the annuity factors become 2.0%, resulting in a difference in road construction cost of 35% and illustrating the importance of capital budgeting aspects. This dynamic view was first introduced in Great Britain (Gayson 1958), where a type of annuity and annual maintenance factors were introduced, expressing the maintenance costs as the ratio of the investment cost. To make the overall cost function consistent, the harvesting volume V, measured in volume units per area unit, has to be converted into an annual harvesting flow volume V^a, which equals the mean annual increment under steady-state assumptions. Introducing these capital budgeting aspects into the total cost function (16), calculating the derivative with respect to road spacing s_r, equalling it to 0, and solving it for s_r, the equation for the generalized optimal road spacing (17) is obtained.

$$s_{r,opt} = \sqrt{\frac{c_r \quad (a+m) \quad 4}{c_s \quad c_{net} \quad c_{offr} \quad V^a}} \tag{17}$$

Where:

s_r road spacing, m

c_r road construction cost, $EUR \cdot m^{-1}$

a annuity factor, a^{-1}

m maintenance factor, a^{-1}

c_s variable skidding cost, $EUR \cdot m^{-1} \cdot m^{-3}$

c_{net} network correction factor

c_{offr} off-road correction factor

V^a harvesting volume flow, $m^3 \cdot m^{-2} \cdot a^{-1}$

(17) gives the basic insight into the main factors affecting the economic efficiency of road network layout. The ratio of road construction to skidding cost (c_r/c_s) is crucial, and inefficient skidding technology calls for lower road spacing. Inefficient road network geometries, expressed by a high network correction factor c_{net}, have a similar effect. A Poisson field layout, yielding a network correction factor of 2.0 (see Segebaden), reduces the road spacing to about 70% compared to a network with parallel roads. Whereas a risky capital budgeting policy (low interest rates) results in relatively high road spacing, low-risk budgeting policies (high interest rates) increase road spacing. Finally, the management intensity – expressed by the harvesting flow volume – is affecting road spacing. Under a plantation forestry regime with an annual flow of about 30 m^3 per hectare, road spacing is half of that under traditional forestry regimes within an annual flow of about 7.5 m^3 per hectare. Although those insights are not new, they cannot be taken for granted.

$$RD_{opt} = \sqrt{\frac{c_s \quad c_{net} \quad c_{offr} \quad V^a}{c_r \quad (a+m) \quad 4}} \tag{18}$$

[18] is the generalized equation to determine the optimal road density, which is the dual problem to optimal road spacing. In 1963, the so-called »Joint Committee« of ILO/FAO/ECE organized a symposium on the planning of forest communication networks that took place in Geneva, Switzerland. Most of the forest operations engineering specialists of that time participated, sharing their knowledge of road network developed from different perspectives. Sundberg delivered a paper on road network economics, reviewing the state-of-the-art of that time (Sundberg 1963). He emphasized that both the network correction c_{net} and the off-road transport correction c_{offr} factors multiply with the theoretical average skidding distance, resulting in higher effective than theoretical distances. He also explained how this should be considered in the calculation of optimal road spacing and roads density,

respectively. Silversides gave an overview on the influence 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 shortest path to the nearest road

⇒ systems where the logs are moving to specific transhipment points (landings) that are located in intervals.

In the seminal book, »Cost Control in the Logging Industry« (Matthews 1942), the author proposed a procedure for the simultaneous determination of road and landing spacing. Assuming that the logs are moving on a radial axis to the landing, the mean yarding distance does no longer equal the distance from the centroid of an area to the nearest road. This called for a more precise estimate of the average skidding distance, which appeared in a report (Suddarth and Herrick 1964). Later, Peters developed an approach that is slightly more precise than Matthews approximation, but quite challenging to solve. Interestingly, the effect of non-efficient road network layout, represented by Segebaden's network correction factor c_{net}, was never considered. This means that all the concurrent landing/road spacing approaches assumed the transport geometry of parallel roads (Fig. 1). The traditional geometric layout of roads and landings assumed that the landings are located on access perpendicular to the roads. Bryer relaxed this assumption by shifting the landing locations on every second road (Bryer 1983). The analysis showed that shifting reduces the average skidding distance by about 5% to 9%, if the ratio of landing spacing to road spacing is between 1.5 and 2.0.

After the 1970s, contributions to the optimal economic layout of road networks became marginal. Whereas some work refined the cost function by including travel cost of workers, the opportunity cost of growth loss due to aisle clearing and other effects (Abegg 1978), most of the work made adaptations to local contexts. There were also contributions that are hardly defendable, such as the consideration of overhead costs in the calculation of optimal road spacing (Thompson 1992). If one formulates a total cost function and finds the derivative for road spacing, only the variables will remain that directly dependent on road spacing. It is not appropriate to formulate an overall cost function, in which overhead costs are directly dependent on road spacing.

The transportation geometry models (Fig. 1, Fig. 2) were all two-dimensional. In order to study how slope affects the road network layout or how the total cost function for a combination of road and off-road transportation increases with slope, a 3D-model must be used. Heinimann developed an approach to differentiate skidder and cable-yarder-based road network concepts on steep slopes (Heinimann 1998). He found that at 30% slope, the skidder-based outperformed the yarder-based total cost function. At 50% slope, the situation was inverse, and the yarder-based outperformed the skidder-based function. This means that there must be a slope at which the minima of both costs functions are equal, which is the threshold, at which a cable-based system is more efficient than a yarder-based one. If context-specific data are available, this approach can be calibrated for different road network concepts. Previously, the discrimination of road network concepts was mainly based on rules of thumb.

4. OR-Tool-Supported Road Network Layout

A high-level panel on decision-making and problem-solving concluded that the way in which problems are presented affects the quality of the solutions that will be found (Simon et al. 1986). In the 1950s, the shift from the pre- to the post-computer era took place, empowering humans to solve problems that were not tractable before. As a consequence, the field of linear programming started to spread into commercial applications, providing methods to identify the optimal solution for a system represented by a set of linear relationships and constrained by linear inequalities or equalities. It seems obvious that this quantitative field of knowledge started to trigger

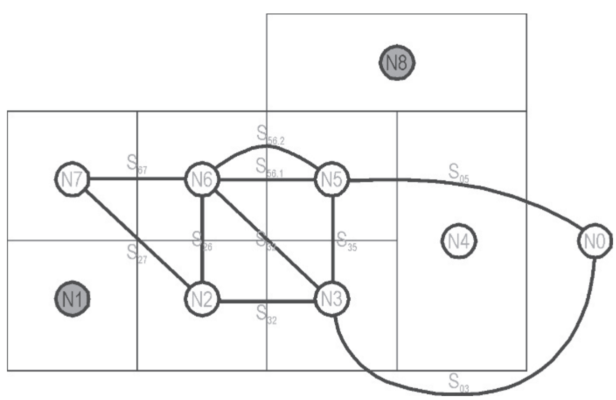

Fig. 3 Conceptual model to integrate silvicultural activities and road construction over multiple time periods, adapted from (Weintraub and Navon 1976)

novel approaches to forest management and engineering. In 1973, a symposium on »Planning and Decision-Making as Applied to Forest Harvesting« took place in Oregon (O'leary 1972) and it paved the way to operations research techniques in forest engineering. Two contributions addressed the use of OR-techniques for road network layout planning (Kirby 1972, Mandt 1972). Fig. 3 illustrates the problem representation, based on which a mathematical program was formulated.

The representation (Fig. 3) relaxes the assumption that the forest cover is homogeneous for the whole area of interest. The area is divided up into similar units (stands, harvesting units, timber stratum), each of which belongs to a specific age class and is managed according to a specific silvicultural regime. The representation further relaxes the assumption that all the roads are built at one point in time, allowing road segments to be constructed in different time periods. The conceptual model (Fig. 3) assumes that each forest unit has one access node (N1–N8), from which the whole unit can be managed. It further defines a set of road segments between the nodes (S_{03} to S_{67}), the combination of which allows the timber to flow from the source nodes (N1 to N7) to the sink node (N0). Whereas Kirby discussed problem formulation options (Kirby 1972), Mandt introduced the analysis of road networks from a network analysis perspective (Mandt 1972), drawing on the then state-of-the-art in the field (Ford and Fulkerson 1962). A seminal paper (Weintraub And Navon 1976) described the problem formulation and solution procedure for the Fig. 3 planning problem. The authors defined sets of (1) access nodes I, (2) road segments J, (3) time periods T, and (4) timber classes K. The problem is to allocate all harvest units ($i_1...i_n$) and the required road segments ($j_1...j_k$) to the time periods ($t_1...t_l$), such that the discounted (revenues – cost) become maximal. While it is not too difficult to transfer this goal into an objective function, the formulation of constraints is much more tricky. The authors found a formulation that could be solved on a mainframe computer in about 2 1/2 minutes (Weintraub And Navon 1976). To keep the solution feasible, the road network had to be restricted to a small number of paths, generated as shortest paths between access and sink nodes (Kirby 1986). Using the classical transhipment problem formulation, large-scale network problems with many links and with many road construction and reconstruction projects could be formulated and solved (Kirby et al. 1979). This model developed into the integrated resource planning model (IRPM) by the beginning of the 1980s, and it became operational for use by the U.S. Forest Service. The model extended the Weintraub-Navon model with traffic flow sets, defining the traffic capacity for a given period and with a set of land-use alternatives instead of timber classes. The solution for the model was feasible for relatively small problem size only, requiring heuristic solution procedures, based on a sequence of the linear program run (Kirby 1986). The authors were aware that such a heuristic procedure would not yield optimal plans except by coincidence.

A review paper on locational issues in forest management discussed the state of models to concurrently locate and schedule both harvest and road network layout (Church et al. 1998). It slightly re-formulates the problem as to model »the scheduling/location which harvest units will be cut in each period, meets adjacency restrictions and ensures that no unit is harvested without the completed road route that can reach the unit«. The authors also discussed the variety of solution techniques used to solve this type of problems, such as dual ascent, Lagrangian heuristics, Monte-Carlo integer programming, simulated annealing, and tabu search. A follow-up paper (Murray 1998) provided a formal mathematical specification for this multiple target access problem (MTAP), emphasizing that a promising exact solution approach be based on the Lagrangian relaxation with branch and bound method.

The integrated formulation of harvest/road-network layout and scheduling made it possible to assess harvesting costs comprehensively, travel cost and road construction and maintenance cost, and to balance the scaling of harvest and roads building activities. However, it still requires the planner to predefine:

⇒ access nodes
⇒ exact location of road segments between access points in the terrain
⇒ detailed layout of harvesting operations beyond each access node.

5. Computer-Aided Road Network Layout Planning

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-

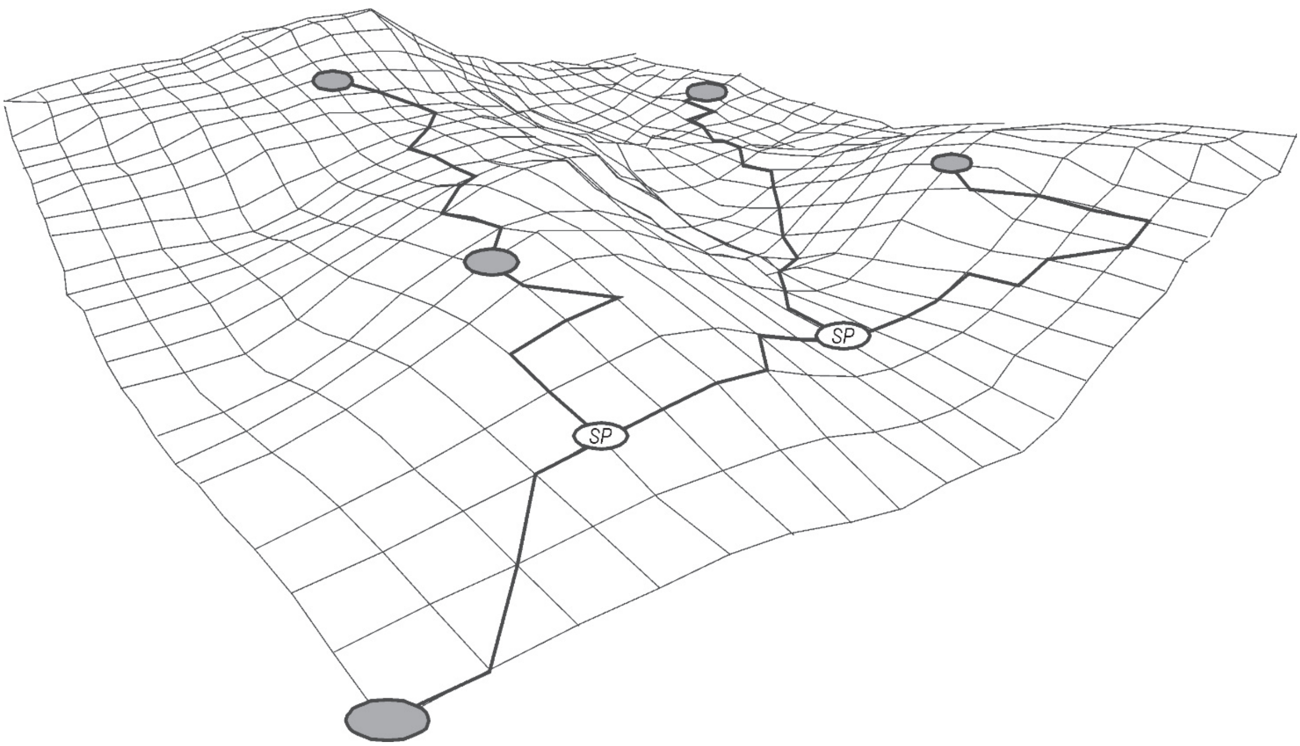

Fig. 4 Automatic road route location on a digital terrain model. From (Liu and Sessions 1993), adapted. *SP* Steiner points; filled circles: mandatory source and sink nodes

ordinate field (Miller 1958), stored electronically. Early applications appeared in the areas of highway earthwork analysis and of highway location (Laflamme 1959). Data acquisition was expensive and laborious, letting the new technology only slowly grow into the broad application. Forest engineering applications appeared in the 1970s, when Burke developed the DTM to automatically extract skyline road profiles (Burke 1974). The situation changed by the beginning of the 1990s, when topographic agencies of many countries started to produce and distribute DEMs systematically.

Fig. 4 illustrates a road layout example on a digital terrain model (Liu And Sessions 1993). Mathematically, a graph is a set of nodes together with a set of edges, each edge associated with two nodes. From a flow perspective, a graph is defined by inflow-, transhipment- and outflow-nodes, all of which have to be identified for the layout of the road network. Traditionally, the planner had to determine those nodes, which were called »control points«, »fixed points«, or »access nodes«. Fig. 4 shows four access and one exit node. After the definition of the nodes, the planner has to identify a pattern of connections between the nodes, such that all »inflow-nodes« are connected to one or more »outflow-nodes«. Traditionally, the solution depended 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 (Robins 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,

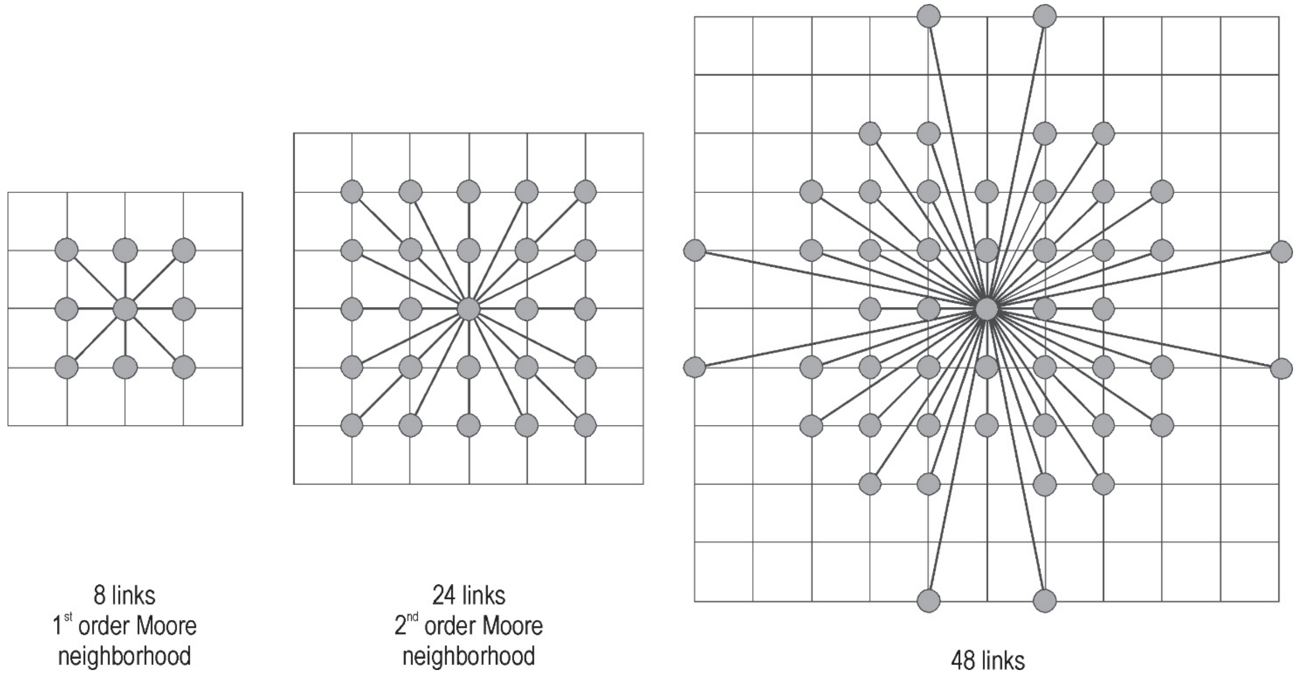

Fig. 5 Link patterns for the automatic generation of road routes on a digital elevation model, following (Stückelberger et al. 2007)

real world terrain, consisting of grid cells and grid points. The guiding idea is to define possible links from each grid point to its adjacent grid points and then to search for a set of serial links that connect the two road network points at minimum cost while maintaining feasibility. The most simple link patterns from one point to its adjacent points are the »Von Neumann« and the »Moore« neighbourhoods (see Fig. 5, left). The solution presented in Fig. 4 is based on a »Moore« neighbourhood, and it results in zigzagging. To our knowledge, a study conducted in Japan pioneered the use of »Moore« neighbourhoods for automatic road network layout (Kobayashi 1984). Liu and Sessions evaluated the feasibility of each link for maximum grade and calculated its construction, transport and maintenance cost, whereas construction cost was adjusted to the side slope. The example in Fig. 4 had 25×25 cells and resulted in about 3300 feasible links. Although the problem size is relatively small, the exact solution for the related mixed integer problem was too time-consuming. This is why a heuristic algorithm was used to solve the problem (Sessions 1987).

The use of an 8-link pattern (Fig. 5, left) results in a quite course discretization of the solution space. Experience in finite element representation showed that both the granularity and geometry matter for the quality of the solution. The eight link-pattern is a low granularity discretization of the solution space that 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.

6. Computer-Aided, Concurrent Harvest Road-Network Layout Planning

The computer-aided, concurrent solution of harvest/road-network layout problems has to combine two NP-hard problems, the plant (harvest) location and a road location problem, which requires a representation in a huge network with hundreds of thousands of nodes and millions of edges (Epstein et al. 2001). A general solution, based on the conceptual model of Fig. 3, was presented in the 1970s (Weintraub and Navon 1976), but the harvest layout activities required to harvest and extract the timber to the input nodes, which were termed access nodes, were not explicitly considered. This calls for the spatially explicit harvest layout model, which was presented in a seminal work in the 1970s (Dykstra And Riggs 1977). Such a design model has to be spatially explicit, dividing the area of interest in a grid of quadratic cells that are usually positioned on a digital elevation model. The problem is then to delineate ground-based and cable-based extraction areas, to locate transhipment points (landings) for tower yarders and skidders in such a way that the majority of cells are accessible, while the cost is minimum (Church et al. 1998). For a given road network, transhipment points have to be located on roads themselves. The concurrent harvest/road-network layout looks additionally to connect all the transhipment points to the exit points.

Weintraub and Epstein, Chilean operations researchers, supported by Bren and John Sessions, did the seminal work to develop the methods and tools to solve the concurrent harvest/road-network layout problem (Church et al. 1998). In 1993, a Chilean state agency, Fondef, started to fund the development of basic operations research tools for the Chilean forest industry. Solving the concurrent layout problem requires the following decisions to be modelled:

⇒ which areas to harvest by ground-based and cable-based systems

⇒ where to locate the transshipment points (landings)

⇒ what area to allocate to each cable system setting

⇒ what roads to build

⇒ what volume of timber to harvest and to transport (Epstein et al. 1999).

To support those decisions with tools, the evaluation of the best-known systems, PLANS and PLANZ (Cossens 1992, Twito et al. 1987), did not perform satisfactorily, triggering the development of PLANEX to solve the concurrent layout problem. Modelling the problem required topographic information of the harvesting area, including timber inventories at an appropriate spatial resolution. PLANEX was designed to interact with a GIS system.

Another paper (Epstein et al. 2006) explains the model formulation and solution in more detail. The modelling philosophy followed a mixed-integer linear programming approach, thus developing a large -sized network design model that uses information stored in cells with a size of 10×10 m. The link pattern (Fig. 5) consists of 16 links, which is close to the 24-link pattern proposed earlier. The approach also considers horizontal alignment constraints, in particular by considering minimum turn radii. The model minimizes the cost of road construction, machine installation, harvesting and transportation and consists of a vast number of sets, parameters and variables. The typical problem involves about 75,000 timber cells, 400,000 potential road segments, and about 300 transhipment points for cable systems and 5000 for ground-based systems. The algorithm to solve the problem is similar to a heuristic to identify Steiner Minimum Trees (Weisstein online-*c*) and produces solutions within an error of about 3.5% compared to exact solutions gained with a commercial solver.

PLANEX has been in use in about 8 Chilean forest companies since the mid-1990s and resulted in savings of 15% to 20% of the operating cost (Epstein et al. 2006). Overall, the use of PLANEX and other operations research tools resulted in annual savings of about US$20 million for the two largest Chilean companies, Bosques Aurauco and Forestal Celco. It is interesting to observe that traditional Central European forestry countries have rarely been using this type of sophisticated systems, thus giving away part of the operational margin and losing competitiveness.

Although PLANEX has been the most widely used system, there are alternatives (Chung et al. 2004, Chung et al. 2008, Meignan et al. 2012). PLANEX has

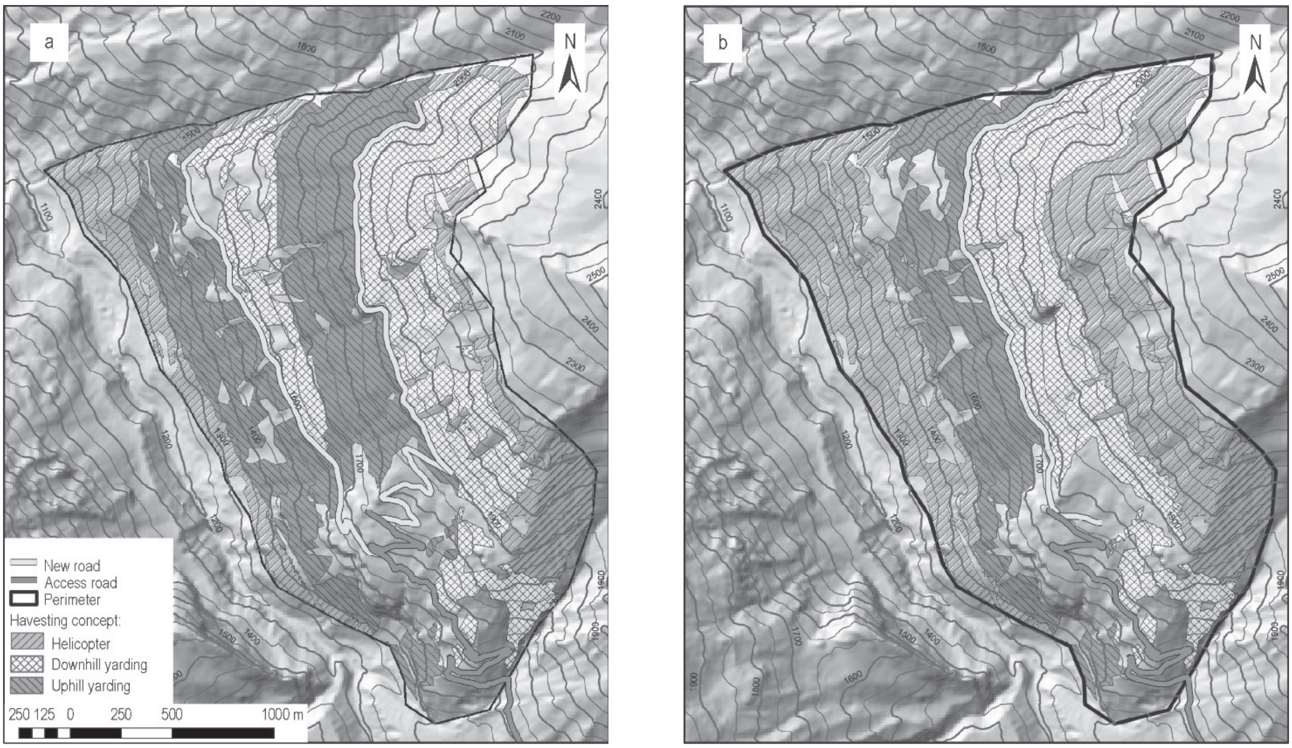

Fig. 6 Comparison of a new exact solution procedure (a) with Epstein's greedy heruistic (b). (a) saves about 7% of the cost of (b). From (Bont et al. 2015). ©2011 swisstopo (JD100042, JA100120)

been using a greedy heuristic (Weisstein online-*a*), and there have been efforts to improve the solution process. A Lagrangian relaxation, decomposing the problem into its two building blocks, resulted in a moderately better approach (Vera et al. 2003). A meta-heuristic, tabu search, which was tailored to the problem led to significantly faster solution times compared to the exact solution with a standard solver (Legües et al. 2007). However, on average, the obtained solutions perform slightly lower than optimal solutions.

Considering that PLANEX was designed for clearcut harvesting systems and is based on a greedy heuristics, Bont et al. (2015) developed a model for the concurrent harvest/road-network layout problem, which was based on a simpler model formulation. They excluded the road transportation cost as a variable by introducing a set cover constrained formulation, which delineated a problem that was much smaller and, therefore, easier to solve than previous formulations. Fig. 6 compares the new, exact solution procedure (a) with Epstein's greedy heuristic (b). The solution for optimality outperforms the greedy heuristic by about 7% regarding cost and results in a different spatial layout. Although the solution performed well, there are still opportunities for improvement. The study demonstrated that the process on primary assigning candidate nodes formed the fitness of the solution as well. At present, the upper feasible limit for a successful solution is less than 1000 ha.

In the early 1980s, the adverse consequences of forest road construction and use started receiving public attention. Studies on how to assess the environmental impacts of forest roads appeared, following the environmental impact assessment philosophy, which was mainly based on expert appraisals. In parallel, the design of forest road networks still followed a mono-objective, cost-optimal approach, which is even true for PLANEX (Epstein et al. 2006, Epstein et al. 2001), the most advanced system to semi-automatically design concurrent harvest/road-network layout. A study (Stückelberger et al. 2006b) developed an approach to map the spatial variability of several objective functions, such as lifecycle cost, ecologically effects and cable yarder landing attractiveness. The weighted sum of objective functions method was used, systematically varying the weights to gain the pareto frontier. The cost-optimal solution is a benchmark, against which eco-optimal solutions were compared. Spatially explicit, eco-optimal solution for bird habitat protection (Caipercaillie) resulted in a length increase of 60% and in an increase of cost of about 80%. Another eco-optimal solution for marshland protection led to an increase of cost and road length of about 30%. Those results illustrated that the minimization of environmental impacts is context-dependent and that there is no overall »silver bullet« solution for the environmental impact problem. Multi-objective optimization approaches improve our understanding of trade-offs, which is crucial for the expert-stakeholder dialogue. Another study (Bont 2012) investigated multi-objective layout problems for mountain protection forests, aiming to concurrently optimize the cost, protection against natural hazards, and residual stand damage. Protection against natural hazards (snow creeping, flow avalanches) requires that cable roads and slope direction be minimized, whereas minimum residual stand damages require uphill logging. Taking the cost-optimal solution as a reference, the »slope-line-optimal« solution resulted in 7% increase in cost, reducing cable roads in slope line directions to zero. The »uphill-yarding-optimal« solution showed a 22% growth in cost by reducing the slope-line impact to zero. To our knowledge, this investigation was the first to semi-automatically generate a concurrent harvest/road-network layout for multiple objectives.

7. Discussion and Perspectives

The present review aimed (1) to bring out the concepts and methods for different road network layout approaches in time, and (2) to identify discontinuities, at which major progress occurred. Our review yielded a set of road network layout methods, covering a path of development that started with rules-of-thumb approaches in the 18th century, and that emerged into semi-automatic mathematical optimization approaches by the beginning of the 21st century. Table 1 shows the characteristics of the different layout approaches

Table 1 Features characterizing different road network approaches. Each vertical sequence of points specifies the profile of a design approach, whereas the shadings indicate major scientific advancements

Representation and design assumptions		Early approaches	Optimum road spacing	Optimal entry point access	CAE network optimization	CAE Harvest road-network layout
Terrain	2D, perfect plane		•			
	2D, contour maps	•	•	•		
	3D, digital elevation models DEMs				•	•
Forest cover	Continuous, uniform conditions	•	•			
	Discrete spatial harvesting units			•	•	
	Discrete harvesting units, represented by a set of grid cells (e.g. 10 m x 10 m)					•
Road network layout design	Expert cognition and techniques	•				
	Expert cognition and experience + mathematical derivation of the key design parameter: road spacing		•			
	Expert cognition and techniques to identify road segments between entry points			•		
	Automatic identification of road segments between entry points				•	
	Mathematical identification of an optimal network			•	•	•
Harvesting layout design	No harvest layout	•	•			
	Manual layout of one entry point for each harvesting unit			•	•	
	Automatic delineation of harvesting technologies (ground- or cable-borne) and generation of a large set of entry points					•

with feature profiles, covering aspects of terrain, forest cover, road network layout and harvesting design.

Early approaches (Table 1) started to get formalized with the appearance of textbooks in the 1870s. They recommended lattice-type networks in flat terrain, the spacing of which relied on rules of thumb. In steep terrain, the definition of a set of access points, which had to be connected by a road network, was an important layout design strategy, although the location of those access points (control points) was not based on scientific evidence, but on very general rules of thumb. The effectivity and effectiveness of those early approaches heavily depended on the skills and expertise of the planning expert. Additionally, road network layout did not take into account the variability of the forest cover and the layout of harvesting units.

In a follow-up phase, the design approaches got scientifically more mature with the introduction of quantitative tools to estimate the optimal road spacing (Table 1). Looking at models of a purely parallel or a Manhattan grid layout, it is easy to see that there is a single design parameter that defines those layouts, road spacing. Starting with seminal work in 1939 (Matthews 1939), a research stream emerged, aiming to mathematically identify the optimal road spacing, which is a dual property to optimal road density. Whereas optimal road density has been mainly used to formulate policies as to what level of accessibility should be achieved on regional or national scales, optimal road spacing has been a design parameter for the spatial layout of specific forest road networks. Although there are tools available to estimate the optimal road spacing, the design of road network layouts for specific terrain units resulted in a small set of network alternatives, of which the most suitable alternative has to be selected. Textbooks on forest road network design that have been widely used, such as (Dietz et al. 1984, Hafner 1971, Kuonen 1983, Wenger 1984) all relied on the manual layout of control points and road spacing as the main network design parameter.

The third type of network design approach – optimal entry point access (Table 1) – emerged in the 1970s, when a new representation of forest road network planning problems appeared. Whereas previous methods neglected the variability of the forest cover and the harvesting layout, the new approach identified harvesting units to be cut in different time periods. Each harvesting unit was characterized by an entry point, to which logs were expected to move by various off-road transport technologies, such as skidding or cable yarder. Once those entry points 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 segments. The search for the minimum tree that connects all the entry points and the sequencing of road construction that considers harvesting activities taking place in different time periods was based on a mathematical 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.

The fifth type of road network design methods – concurrent harvest/road network layout (Table 1) – stems from the DEM-based CAE network optimization method by integrating the harvest layout and concurrently solving the harvest/road network layout problem. Funded by a Chilean state agency, a team of Chilean and U.S. researchers developed PLANEX, a system that semi-automatically generates harvest/road layouts for specific forest areas that are near-optimal. Eight major Chilean forest companies have been using PLANEX, which resulted in significant cost savings within the industry. While this methodology was designed for clear-cutting regimes in a plantation forestry context, it was an obstacle for the transfer to areas with close-to-nature forestry schemes. Around 2005, research emerged, aiming to improve the efficiency and accuracy of the automatic road segmentation on a DEM, to adapt the problem formulation to close-to-nature and continuous cover silvicltural regimes, and to solve the problem exactly for optimal results. However, more recent network design methods have mainly been used for case studies. The reasons for this limited use are the high level of road network development and the fact that the road network specialists lack skills for using quantitative, OR-based methods.

The feature profiles in Table 1 show the major scientific advancements in forest road network layout in the last 150 years. The first advancement was the emergence of the theory of optimal road spacing/density, which matured between 1940 in 1960 allowing a scientifically informed layout of road networks. The second advancement, maturing in the 1970s and 1980s, represented the road layout problem as a timber flow problem from entry nodes (harvest units) to exit nodes for a set of time periods, which became known as Multiple Target Access Problem (MTAP). While the location of entry/exit nodes and harvest volumes had to be located and estimated by the planner, a mathematical optimization program yielded the best possible connections of entry to exit nodes. The third advancement, triggered by the broad availability of Digital Elevation Models (DEMs), developed methods to automatically identify the minimum cost road path between any pair of entry points, providing detailed information to determine the optimal minimum-cost connection between entry points and exit points. The fourth and most recent advancement integrated two spatial layout problems – road network and harvest design – representing harvesting units as a set of grid cells, from each of which logs have to »flow« on the minimum cost path to the exit nodes. This latest development reconciled different technologies, such as geographical information, digital terrain and mathematical optimization technology that require operations research and engineering knowledge.

Any review of past developments raises the question of how the observed trends could continue into the future. Considering that operations-research-based road network layout approaches have been mainly in use under clear-cut and plantation management regimes, the OR-based and the traditional forest road layout community have been unlinked. Whereas the road layout optimization community is exchanging its knowledge in the operations research publications, the traditional forest road layout community still relies on forest publications. The separation also affected education and training, and there are still forest operations courses around the world that are mainly focusing on the traditional road spacing approaches relying on OR-based methods only marginally or even neglecting them. This calls for an adaptation of road network layout courses and related training programs for forest road specialists across countries, or even across continents. The further development of all OR-based road network layout methods for multi-objective settings is the second path for improvement, which allows for the identification of pareto frontiers that quantify very present trade-offs between efficiency (cost minimization) and environmental impact objectives. An improved representation of the terrain surface is a third path for improvement that could stem from finite element theory. The approaches reviewed above are all based on a regular, lattice -type discretization of the terrain surface. Finite element theory provides a broad experience of how to best represent the surface with a mesh (Lo 2015), and triangular irregular networks (TIN) are a class of surface meshes that are superior to lattice-type meshes. Their advantage is that the granularity of basic elements (triangles) increases in areas with high variation in height, and decreases in regions with low variation. We hypothesize that moving from lattice -type DEMs to TINs or even more sophisticated meshes (Lo 2015) will further improve the quality of the solutions. The integration of road network layout with detailed road engineering is a fourth path for improvement. Road network layout identifies corridors, within which the future centreline of road will be located. The availability of Digital Elevation Models (DEMs) that are derived from airborne light detection and ranging (LIDAR) systems are offering new opportunities. The availability of unmanned aerial vehicles (UAVs) and low-mass LIDAR sensors with masses of less than 5 kg brought significantly down the cost for the development of high-resolution digital elevation models (Favorskaya and Jain 2017). A future scenario could be as follows: based on an optimal or near-optimal road network layout, a UAV-borne LIDAR sensor could scan all road corridors, producing geo-referenced point cloud, out of which a high-resolution DEM could be extracted. Detailed road engineering starts with the location of a traverse, which is defined by intersection points, which is followed by the definition of the vertical alignment. Traditionally, those two activities had to be done manually, and only about 10 years ago scholars proposed a semi-automatic procedure with the capability to concurrently optimize horizontal and vertical alignments, aiming to minimize construction and maintenance cost (Aruga 2005). Integration of road network and detailed road engineering is expected to further reduce construction, maintenance and transportation cost. The refinement of optimization techniques is the fifth path for improvement. Even one of the most sophisticated systems, PLANEX, is based on a heuristic solution technique, which is providing near-optimal, but not optimal solutions. The increasing performance of computers and the power of optimizers to solve large mixed-integer problems to optimality has been a trend that will continue. However, we should not forget that smart model formulation and the tuning of integer programming algorithms have a considerable potential to reduce solving time and to make problems tractable, resulting in feasible or near-optimal solutions (Klotz and Newman 2013). Set cover problem formulations are a promising approach to decrease the problem size and to achieve optimal or near-optimal solutions (Bont et al. 2015). Finally, it is still unclear how the scientific developments from the early transport geometry approaches (Launhardt 1872, Schuberg 1873) spread and evolved into the traditional layout theory, represented by traditional textbooks (Dietz et al. 1984, Hafner 1971, Kuonen 1983, Wenger 1984).

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