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Fifty years of operational research in forestry

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Abstract

This paper describes operational research (OR) contributions in forestry over the past 50 years, based on scientific pathways along which the authors have traveled. We draw on our personal experiences and recall how the use of OR in forestry has evolved from the early use of linear programming in the Canadian forest products industry in the 1950s and strategic forest management planning by the U.S. Forest Service in the 1960s. We describe the widespread use of OR in many aspects of forestry over a 50-year timespan (1970–2020) and to the present day, where climate change and biodiversity challenges and increased data availability are important. The paper covers many areas of forestry, including forest management, natural disturbance processes, tactical and operational harvesting, transportation, and value chain management. Each section in the paper includes a historical description of OR-based key applications as well as OR-based model and method developments Additionally, we discuss our perceptions of OR in future use and its importance in forestry.

Keywords: forestry; operations research; operational research

1. Introduction

The forest industry is of great importance in many countries, generating significant revenue and contributions to each country's gross domestic product (GDP) and creating jobs for a large proportion of the workforce, often in rural areas. The industry produces many products such as paper, lumber, and energy. Forests provide many ecological benefits, including carbon sequestration, water quality enhancement, and biodiversity conservation. Forests can

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be a sustainable source of timber, pulp, and other forest products when properly managed while also maintaining major ecosystem services. Operational research (OR) is an interdisciplinary field that draws upon mathematical and statistical modeling, optimization, computer simulation, and other analytics techniques to help solve complex problems in many industries. Operational researchers have played key roles in forestry by working on a diverse array of decision-making problems within various types of organizations over the years while tackling theoretical and applied problems. OR applications in forestry also need to interact with many specialists in other fields, such as foresters, biologists, engineers, fire specialists, and ecologists.

Terms used to characterize operational researchers have evolved over the past 50 years. Often, "management science" (MS) was coupled with OR during the 1970s and 1980s, that is, MS/OR. In the 2010s, INFORMS adopted "analytics," defining it as "the scientific process of transforming data into insights for the purpose of making better decisions" (informs.org) and used the term to describe OR in the traditional context. Analytics is often separated into four different stages: descriptive, diagnostic, predictive, and prescriptive, each depending on the level of difficulty and value for the users. OR, MS, and analytics have been used in forestry for a long time; they have been applied to various forestry and forest management decision-making problems over the past 50 years. Applications have often been motivated by practical use, and many models and methods have been implemented in planning and decision support systems. In some cases, the theoretical developments that flowed out of OR applications to forestry problems were applied in other industrial areas (e.g., mining, fishing, agriculture, and petroleum). OR research is carried out at and applied in a variety of companies, research organizations, academic institutions, and government organizations. Often, there is a rewarding symbiosis among various stakeholders.

OR and analytics have been used in several forestry areas. In forest management, OR models are used to identify optimal timber harvesting or silvicultural treatment schedules that include activities such as final felling, thinning, and planting decisions. These decisions support managers who must resolve decisions to maximize the economic, environmental, and social benefits of forest management. OR has applied to other important forest management problems, including biodiversity conservation, that is, setting areas aside for wildlife habitat management purposes, fire management, and carbon sequestration.

Many logistics problems complicate forest value chain management, and OR can be applied to these problems, starting with harvesting processes and ending with finished product distribution to customers. The divergent characteristics of the forest logistics chain where there are few products at the start and many in the end make problems hard to manage and plan. Mathematical optimization and simulation models can be used to help minimize costs, maximize values, reduce CO_2 emissions, and improve efficiency. The forest sector is also subject to many risks, including climate change impacts, natural disasters, and market fluctuations. OR can be used to develop risk management strategies that help foresters mitigate such risks and improve their resilience. OR can help managers anticipate, prepare for, and manage potential risks when specific scenarios materialize by using mathematical models to analyze various scenarios.

Strategic, tactical, and operational planning are commonly associated with long-, medium-, and short-term planning. For example, strategic planning in transportation may cover a five-year planning period for investment in a new machine system. Such planning horizon would be classified as

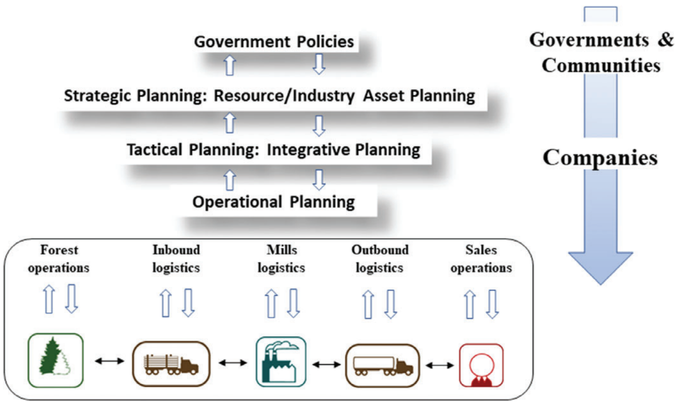

Fig. 1. Illustration of the hierarchical planning structure from strategic planning with government policies down to operational planning.

tactical planning in forest management. Though the strategic forest management model takes place over 100 years in some forest regions (e.g., boreal forests), a number of variables are not real-life business decisions to be implemented in many models but capture the potential impact of business decisions. Consequently, though a model may span a planning horizon covering more than 100 years, business decisions are made and implemented over much shorter time periods (e.g., a few years). We and our colleagues have sometimes classified planning models as strategic if business decisions took place over one or more years, tactical if models covered one- to 12-month planning horizons, and operational if decisions were made during periods lasting less than a month. In addition, we may have used real-time decision models covering business decisions made in a few minutes. We noted a wide and overlapping use of terms in the scientific literature. Figure 1 illustrates the interactions between different planning levels from strategic down to operations. In the figure, we also include government policies as the longest term as it has a large influence on any strategic planning.

Many international scientific conferences have served as major venues for knowledge transfer and collaboration. Some conferences, such as the annual INFORMS and the *Association of European Operational Research Societies* (EURO) conferences and the triennial *International Federation of Operational Research Societies* (IFORS) conferences, are more general, whereas others are more specifically geared to forest applications, such the *Symposium on Systems Analysis in Forest Resources* (SSAFR) for forest logistics, *Council of forest engineering* (COFE) for forest operations, *INFORMS Section on Energy, Natural Resources, and the Environment* (ENRE) for connection to other natural resource areas, and *International Union of Forest Research Organizations* (IUFRO) for general forestry. Forest applications have also been presented at various specialized conferences on transportation, routing, logistics, and value chain management, and the research contributions are published in many scientific journals. Some of the more noted specific forest journals include the *Canadian Journal of Forest Research*, *Forest Science*, *Forest Policy and Economics*, *Scandinavian Journal of Forest Research*, *International Journal of Forest Engineering*, and more general OR journals such as the *International Transactions in Operational Research*, *Operations Research*, *European*

Journal of Operational Research, and *Journal of the Operational Research Society*. Many of these journals have put the spotlight on various forestry problems.

In addition to journals, books have described OR development more broadly. *The Handbook of Operations Research in Natural Resources* edited by Weintraub et al. (2007) provided an overview of OR models and methods in natural resources, including forestry. Part of the book covered many topics such as forest management, harvesting, transportation, fire management, multicriteria optimization, and forest economics. *The Management of Industrial Forest Plantation* by Borges et al. (2014) presented research results relating to the practice of forest management, covering forest supply chain components ranging from modeling techniques to management planning approaches and information and communication technology support. *Forest Value Chain Optimization and Sustainability* by D'Amours et al. (2016) provided a global perspective on many challenges the industry needed to face and provided some key global strategies that could help professionals cope with global challenges, such as collaboration, strategic value chain planning, and interdependency analysis.

The authors who contributed to those books have multidisciplinary backgrounds and different types of affiliations. Many authors are affiliated with universities noted for specific forest faculties (e.g., Swedish University of Agricultural Sciences, University of British Columbia, Université Laval, University of Natural Resources and Life Sciences, and Oregon State University), whereas many others work within various university faculties or departments such as engineering, business, economy, mathematics, natural resources, and computer science with an emphasis on specific forest applications. Some authors work directly with forest companies, of which many, if not most, are involved in industrial case studies. Research organizations are other key institutions that work closely with forest companies and typically receive partial government funding. Organizations include, e.g., the Forestry Research Institute of Sweden, Skogforsk (Sweden), FPInnovations (Canada), LUKE (Finland), and Scion (New Zealand). Federal and provincial government bodies are also key, such as the United States Department of Agriculture (USDA) Forest Service, Natural Resources Canada, and Ministère des Forêts, de la Faune et des Parcs in Quebec (Canada). We can also mention International Union of Forest Research Organizations (IUFRO), an international network of forest scientists in forest-related research that enhances understanding of the ecological, economic, and social aspects of forests and trees.

The objective of this paper is to provide readers with an overview of OR contributions to forest and associated forest value chain management. As noted earlier, we did not intend to provide readers with a comprehensive review or current state-of-the-art article; instead, we decided to provide an overview of OR adoption in forestry over the past 50 years viewed from the authors' experience. Consequently, we do not cover many areas—or these areas are described from our perspectives or background. We largely put emphasis on the forest and parts of the forest value chain that link forests to mills, not production process control at and within mills. The planning horizons range from very short (i.e., a few minutes for dispatching solutions in routing) to several hundred years in strategic forest management planning over many forest rotations. The paper covers strategic forest management, natural disturbances, tactical and operational harvest planning, transportation planning, and value chain planning. Each section consists of a small number of subsections that describe the main developments in the areas over the past 50 years (models, methods, and applications). We also include a section that discusses our anticipation of some major future challenges and end with some concluding remarks.

2. Brief history of OR in forestry

Bare et al. (1984) described the paper trim problem by Paull and Walter (1954) as "perhaps the earliest reference to the use of systems analysis-OR in the forest products industry" in a paper abstract presented at a joint meeting of the Econometric Society, the American Statistical Association, and the Institute of Mathematical Statistics in Montreal in 1954. In a later article entitled "Linear programming: A key to optimum newsprint production," which appeared in the *Pulp and Paper Magazine of Canada* issue in January 1956, Paull (1956) indicated that "Abitibi [a Canadian forest products company] has been and is still making use of linear programming in two important applications: transportation scheduling and trim scheduling." Other important early OR work in forestry was carried out by Balas in Romania in the early 1960s. In the paper in which he described his additive algorithm, Balas (1965) said that he had applied to "a problem in forest management," and that he had published a description of that work in Balas (1963). Later, Rand (2011) described that first application in more detail—that it was to solve an important class of forest management transportation models—the design of a road network to access forest stands that were to be harvested.

OR development in forestry over the past 50 years was not only influenced by general methodological developments but also applied to specific forestry problems. An illustrative review of quantitative methods between 1950 and 1984 can be found in Bare et al. (1984). The 1970s promoted the development of linear programming (LP) solvers and matrix generators for forest management or network flow problems. Based on the simplex method, solvers for LP models were often developed at companies and organizations in house. More advanced and commercial solvers were developed in the 1980s, such as Cplex for LP and mixed integer programming (MIP) models and Minos for linear and non-linear optimization problems that made it possible to solve larger optimization problems, whereas larger decision support systems were developed in the 1990s. Advances in Geographic Information Systems (GIS) and remote sensing technology enabled the incorporation of spatial data into forest management optimization models, leading to the development of spatially explicit models for harvest scheduling, habitat conservation, and landscape-level planning. The use of GIS has also supported transportation, harvesting, and other important value chain activities. The increased awareness of climate change has led to the development of models that include carbon sequestration and approaches to include risks or management principles related to fires, droughts, insects, and wind throws. The practical use of OR techniques increased in many countries. In Chile, for example, the forest industry saw many OR models used successfully for decision making in integrating harvesting and road building (Optimed), machine location and road building (Planex), short-term harvest and bucking decisions (Planex), and daily routing of logging trucks (Asicam). These systems won the Franz Edelman in 1998 (Epstein et al., 1999a); some of these systems are still in use.

Various heuristic methods that solved large MIP models for specific applications were also developed in the 1990s. A number of general modeling languages that facilitated optimization model development and connections with input data were developed, too, such as GAMS (www.gams.com), AMPL (ampl.com), and LINDO (lindo.com). Such modeling languages facilitated much model development in forest logistics problems. In the 2000s, supply chain management or value chain management concepts were introduced in many industrial sectors, enabling a more systematic and holistic approach to be used in supporting integrated planning, which spanned multiple activities. These concepts made handling multiple objectives, uncertainty, and various levels of collaboration among stakeholders in the forest value chain easier. The use of light detection and ranging (LiDAR) made it possible to collect very detailed and spatially explicit data for forests, including digital terrain models, forest density, and growth. As the focus on sustainable forest management increased, multiobjective optimization techniques, such as goal programming and Pareto optimization, emerged to make the balancing of competing objectives, such as timber production, biodiversity conservation, and carbon sequestration, easier. Such techniques have enabled forest managers to consider ecological and social aspects alongside economic factors in their planning processes.

The Industry 4.0 concept that integrates digital and human systems was introduced in the 2010s. This enabled and supported autonomous operations in machines. Here, the digital twin concept can be used, where a digital description of the real system is applied to many experiments and testing before its implementation in the actual system. At the same time, many diverse data sources have emerged, creating big data that can be compiled and used for many multidisciplinary forest applications. In general, we can identify a time gap between model and method development and its implementation in a practical planning system. A model and method can be developed successfully but integrating the model with the required data and quality levels, visualization or report generation of results, practical user interface, and central company enterprise resource planning (ERP) systems presents many challenges that need to be overcome before either can be used in practice. Fortunately, many such systems have been developed by software companies, forest companies, and other organizations. Overall, the use of OR in these systems is a critical component. The past decades have also seen an increase in considering multiple objectives and stochastic models, as decision making has increasingly been incorporated into multiple areas of concern, uncertainty in markets, tree growth (Alonso-Ayuso et al. 2011; Veliz et al., 2015), and in particular the tremendous uncertainty in forest fires. Owing to climate change, uncertainty in forest fires has been upgraded to a major factor of disturbance in forests and large areas of population. Figure 2 provides a timeline highlighting the main milestones described in the paper.

3. Strategic forest management planning

Strategic forest management models highlight interaction between forest-management decisions, such as harvest scheduling, and issues such as sustainability, preserving biodiversity and ecosystems, soil and water quality, social issues, and economic returns. Figure 3 gives one forest area in Quebec (Canada) that is subject to such strategic planning. These models support long-term decisions (typically at least one cycle, where a cycle is the time between planting and harvesting) and explore policies related to the whole estate. Strategic planning takes place at the industry and government levels.

Although many papers describing the use of OR in forest planning had already been published, the first applied OR model was Timber Ram (Navon, 1971). The model was used by the U.S. Forest Service (a federal agency under U.S. Department of Agriculture) in its harvest planning that was carried out every 10 years. The U.S. Forest Service owned the lands but sold the harvested timber right to private forest firms that were in charge of harvesting. The U.S. Forest Service used a

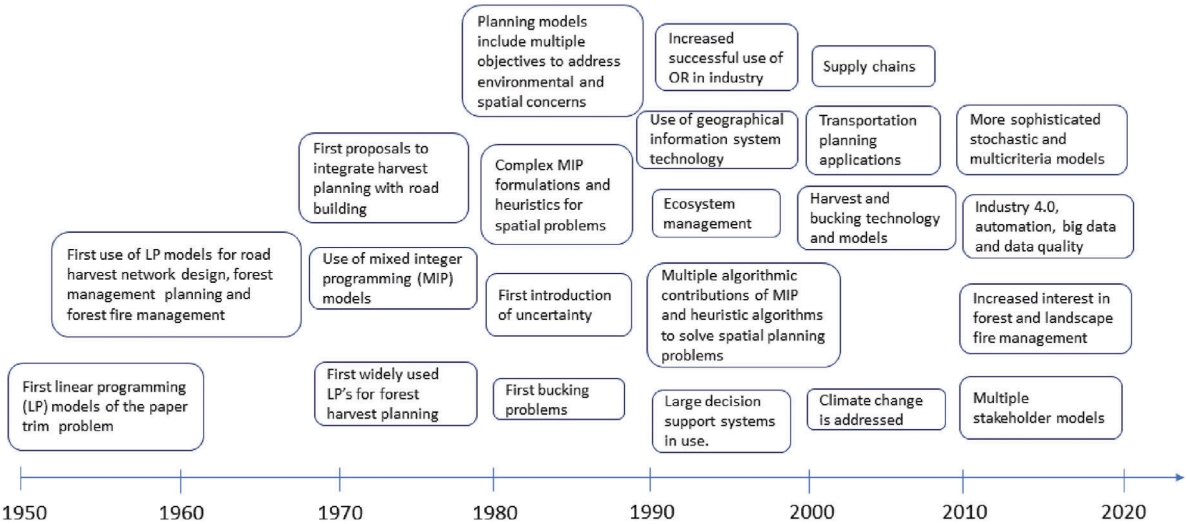

Fig. 2. Timeline of the main milestones of operational research (OR) in forestry.

Fig. 3. Illustration of a typical forest area for which strategic forest management plans are developed. Photo by Mikael Rönnqvist.

deterministic simulation model to evaluate many harvesting options before offering timber for sale. There had already been working on projecting future yields (m^3/ha) depending on the treatment. This work was mostly thinning, where a percentage of relatively young trees are harvested, provide timber, and enable remaining trees to grow better, and clearcuts, where the whole unit or stand is harvested. The U.S. Forest Service faced political pressure to increase the amount of timber sold. To protect the forest industry, the U.S. Congress passed a law that compelled the U.S. Forest

Service to plan its timber sales in a non-declining yield fashion. If the planned harvest volume was a certain level in a decade, the volume could not fall below said level by any small percentage during the next decade (e.g., 2%). This law forced the U.S. Forest Service to reduce harvested volumes to satisfy non-declining yield principles, which was widely considered a good measure that came with complex consequences. Given the non-declining yield constraints, the set of feasible solutions was relatively small; when simulation models were used to evaluate proposed harvest plans, planners could not find feasible solutions. This scenario called for the use of LP, leading Navon and colleagues to develop the first widely used forest harvest scheduling LP model that was labeled Model I.

Model I called for a set of alternative management options (e.g., harvesting, regeneration, and silviculture schedules or prescriptions) to be specified for each forest stand or homogeneous compartment over a planning horizon that might extend over one or more harvesting and regeneration cycles that covered more than 100 years in some cases. This planning approach was judged extremely successful, leading the U.S. Congress to pass another law that compelled every state in the United States to use Timber Ram in their harvest planning—this was probably the only time Congress law compelled the use of OR. One shortfall of Timber Ram was that it addressed few environmental considerations other than to prohibit harvesting in some designated areas. The U.S. Forest Service later developed new models, such as FORest PLANning (FORPLAN), that included explicitly basic environmental considerations. FORPLAN is a large-scale LP system used to support national forest land management planning. Kent et al. (1991) further described experiences from this system.

Each management plan has an economic value, which is usually the net present value of plan implementation. The LP model solution produces a solution that will maximize the net present returns subject to constraints (e.g., the area allocated to all prescriptions cannot exceed available area and the aforementioned non-declining yield constraints, that is, other constraints related to limiting the variation in harvest volume from period to period and not harvesting some areas for environmental reasons). These constraints are relatively easy to formulate, and the LP problem is easy to solve given the requisite forest growth and yield, cost, and revenue data. No significant consideration was given to uncertainty in relation to future markets and price conditions, timber growth, and fire losses until later. Uncertainty was later studied using chance constraints (Weintraub and Vera, 1991; Hof et al., 1992) and the use of scenarios to represent uncertainty (Alonso-Ayuso et al., 2011; Veliz et al., 2015). Another major model parameter to be specified is the discount rate used to compute the present net worth of future revenues and expenditure—a crucial choice as forest management revenues and expenditures are earned and incurred over planning horizons that commonly extend beyond 100 years. A discount rate lower or higher than actual volume growth is a key characteristic, as it pushes harvesting decisions back or forward in time.

Alternative models were proposed as illustrated in Gunn (2007). In Model II, stands harvested during the same period are grouped into one stand and treated as one from that period. Model III is more detailed, where all stands of the same age are aggregated, and in each period, the land in a class age is harvested, reverting to a new planting age or growing one period older. Since aggregated stands may not be close enough to each other, thereby making it difficult to consider joint harvesting in the next cycle if they have different soil characteristics, some ambiguity is to be had in Models II and III. The analyst needs to decide which model to use, though Model I would appear to be the most popular because of its simplicity.

Environmental concerns grew in importance in the 1980s and 1990s; unsurprisingly, they continue to grow in importance today. The U.S. Forest Service developed new forest management planning systems such as SPECTRUM (Greer and Meneghin, 2000), which explicitly included non-timber values. The importance of non-timber values has grown to the point that in some states across the United States, timber harvesting has been all but banned. In industrial plantations, typically pine or eucalyptus, forest companies need to certify that they are complying with environmental restrictions, and they do so by adhering to forest certification administered by third-party forest certification organizations such as the Forest Stewardship Council and the Sustainable Forestry Initiative.

Commonly considered non-timber values include wildlife conservation, soil conservation, water quality, scenic beauty, and recreation. These values created a need for spatially explicit forest management plans, the earliest versions of which included adjacency constraints that limited harvest blocks to some maximum size (e.g., 40 hectares) and prohibited the harvesting of adjacent stands until the first of two adjacent stands reached some minimum age—commonly referred to as a “green up” constraint, leading to the creation of “checkerboard”-type patterns on the landscape. The optimization of such spatially explicit forest management plans requires the formulation and solution of computationally challenging combinatorial problems that have caught the attention of many researchers and led to the publication of many research papers. This is discussed in a later section.

Strategic planning needs to increasingly incorporate decisions into part of or the whole production chain. This chain may include availability of raw materials, economies of scale, markets, social aspects such as Indigenous peoples’ rights, and the effect of climate change, leading to more complex decision making with multiple objectives and additional uncertainties. Climate change can induce uncertainty in multiple aspects that include tree growth and market characteristics. Defining scenarios is one way of incorporating these uncertainties, as these scenarios represent a climate through the horizon in each period. Solutions maximize expected net return and are feasible for all scenarios (Garcia-Gonzalo et al., 2020). Other factors, such as carbon sequestration, land erosion, and wildlife protection, may also be of importance, leading to multicriteria stochastic models. Risk aversion could also be considered in some cases (Alvarez-Miranda et al., 2018).

There may be many ecosystem services to include in long-term forest management. In these cases, a balance must be struck between objectives by multiple stakeholders and conflicting objectives. Consequently, approaches must be developed to pinpoint this kind of weighting. Many approaches are based on multicriteria analysis. For example, the analytic hierarchical approach (AHP) involves decision makers making pairwise comparisons as a basis to identify the best weights. Nilsson et al. (2016) described how multiple-criteria decision analysis, including AHP, can be used efficiently in cases with multiple stakeholders. Many efforts develop decision support systems. An approach for participatory planning proposed in Quebec is to use the so-called decision theater (Boukherroub et al., 2018), which brings all relevant stakeholders together in the same environment and provides advanced planning and visualization tools for a quick planning and acceptance process. Nowadays, many debates on traditional forest production and their impacts on biodiversity goals are sparked. Models to evaluate and

Fig. 4. Wildfire in the boreal forest region of the province of Ontario, Canada. Photo by David Martell.

manage these debates have been analyzed and can be found in Eggers et al. (2022). Many planning software programs are available to support planners in long-term forest management. Examples include the Woodstock software (remsoft.com) and the Heureka system (Wikström et al., 2011); each system has different capabilities and modules that deal with a variety of objectives.

4. Natural disturbance processes

4.1. Dealing with uncertainty generated by natural disturbance processes

Forest management takes place across diverse spatial and temporal scales in areas that range in size from small parcels of land (e.g., plantations or woodlots) to large industrial forest management units (FMUs) covering several hundreds of thousands of hectares in size. The planning horizons range from days to weeks, months, years, or decades, and in some cases (e.g., in boreal forest regions) more than 100 years. Forests are impacted by both human activity—for example, road construction and land clearing for urban development, human-caused fire occurrence, and industrial harvesting—and natural ecosystem disturbance processes—for example, fire, insects, disease, and wind. Forest managers have long recognized the need to account for uncertainty in their planning (e.g., Gaffney, 1960), but early forest regulation methods (e.g., Pearse, 1967) and early OR applications to forest management planning (e.g., deterministic LP models such as Timber Ram) could not and did not explicitly account for such uncertainty. Figure 4 illustrates the natural disturbances with a forest fire.

Of course, many sources of uncertainty impact forest management but consider the impact of fire on timber production. Forest managers divide their planning horizons into discrete time periods (e.g., years or decades) and develop aspatial or spatially explicit strategic harvesting schedules that specify how much area is to be harvested during each period to produce specified amounts of industrial fiber for mills over their long planning horizons. Those plans are designed to minimize the cost of delivering relatively stable flows of wood to mills that produce lumber, pulp and paper, and other forest products. Although most forest companies maintain some buffer stocks of harvested trees in the forest en route to the mill and in their mill yard itself (i.e., logs), these stocks are costly and are primarily used to smoothen minor disruptions in the log supply to mills caused by short-term wood transportation disruptions because of weather (e.g., spring thaw) or heavy rainfall events that wash out haul roads, not significant fire losses.

When a wildfire burns a large portion of a FMU in which harvesting is taking place, the company depending on that wood will have to determine how best to cope with that loss. In the short run, the company might choose to move their harvesting equipment to unburned areas, the harvest of which had been planned to take place later, and in some cases, they might have to quickly construct new roads that they had not planned to construct until sometime later. In the long run, the company will have to develop a new strategic plan based on the "new" partially burned forest that contains less merchantable fiber than the unburned forest. Both results will reduce forest value of the forest and the sustainable harvest level. The greater the likelihood of such losses, the greater the need to incorporate these potential losses into forest management planning processes.

Van Wagner (1979) developed a deterministic model to illustrate how the impact of a fire could and should be evaluated from a forest-level perspective but did not consider how the uncertain occurrence of fires could be incorporated into such models. Martell (1980) pointed out that no stand or forest-level planning models account for uncertain fire losses, though some probabilistic forest management models had been developed (e.g., Lembersky and Johnson, 1975). Gaffney (1960) suggested the possibility of burning should lead to decreased rotation intervals, and Martell (1980) extended a stand-level stochastic forest rotation model that accounted for probabilistic fire losses proposed by Wagner (1969).

The important "unsolved" problem that remained, however, was incorporating uncertain fire losses in forest or landscape timber strategic planning models—a novel solution developed by Reed and Errico (1986) that Martell and his colleagues subsequently adopted and labeled Model III. Reed and Errico (1986) drew on their demographic and ecological modeling backgrounds and modeled a forest as a network in which a portion of each age class could either be harvested, grow up into the next oldest age class, or be burned down into the youngest age class. Martell (1994) subsequently used the Reed and Errico (1986) model to assess the impact of fire on timber supply in Ontario, and Boychuk and Martell (1996) used the model to develop an aspatial multiperiod stochastic programming model of a flammable forest.

Fire is but one of many natural disturbance processes that impact forest management. Insects, disease, and weather may not be as spectacular and photogenic as wildfire nor do they pose serious threats to public safety in the short term (except severe weather), but they can and often do significantly impact harvest operations, transportation flows, and forest values.

Insects are a major natural disturbance in many forests. Two examples of insects are the eastern spruce budworm (*Choristoneura fumiferana*) in the boreal forest region of Eastern Canada and the mountain pine beetle (*Dendroctonus ponderosae*) in Western North America. When an area is infested by spruce budworm, it is important to estimate what level of infestation each area has to evaluate mortality probabilities and recoverable values. Such information can inform decisions concerning the areas in which salvage harvesting should take place, which areas to spray, and which areas to leave. Such a model was developed by Mushakhian et al. (2020).

Storm damage caused by wind, producing large areas of "blowdown," and freezing rain (i.e., ice storms) is another major natural disturbance process. Blowdown areas marked by still partially rooted trees are strewn in random patterns, making them not only very difficult to harvest using mechanical harvesting systems designed to harvest relatively homogeneous stands of standing live trees but also dangerous, as they pose serious safety threats to the workers involved. Blowdowns are much more flammable than healthy forest stands; they are not only more likely to burn before they can be salvaged but are also potential sources of high-intensity wildfires caused by lightning or the harvesting activity itself. These wildfires can spread into surrounding healthy stands. Given the primary and secondary effects of storm damage, these situations must be dealt with quickly. Decision support tools are therefore needed to inform the rapid reallocation of machine systems, establish new terminals for intermediate storage, develop new harvest schedules, and identify new customers who can make use of the increased amount of fiber. Broman et al. (2009) provided an example of how OR tools have been used to support such planning. It is also important to address the related need for continuously updated information to support continuous replanning. The importance of secondary interactions and impacts of natural disturbance processes must also be considered since tree mortality caused by insects, disease, and storm damage can increase the landscape's flammability.

4.2. Mitigating the potential impact of uncertain natural disturbance processes

Forest managers can mitigate the impact of natural ecosystem processes; operational researchers have been helpful in this matter. Take, for example, forest and wildland fire management. Shephard and Jewell (1961) published what we believe are the first OR applications to forest fire management, followed by many others whose contributions are described in Martell's (1982) review of OR studies in forest fire management.

Many forest and wildland fire management agencies were established in response to tragic losses of lives, forest resources, and other values and driven by what was characterized as "fire exclusion" policies, that is, fire was bad and needed to be excluded from forested landscapes at almost any cost. Fire management agencies and OR specialists who worked with them put their attention on preventing human-caused fires from occurring, detecting human and lightning-caused fires at small sizes, acquiring suppression resources (e.g., air tankers and fires fighters), pre-positioning them to support their initial attack objectives (e.g., to contain fires at very small sizes), and containing the growth and impact of large fires that escaped initial attack.

Heineke (1973) explored fire prevention from a utility theory perspective, and other economists studied fire prevention, but the OR community has for the most part ignored wildfire prevention. We believe prevention has largely been ignored because of the difficulty of developing prevention production functions. Peter Kourtz developed many models to inform detection system management, one of which was a dynamic programming model to inform aerial detection management, that is, which flight lines should be flown by a fixed-wing aircraft and require an infrared detection system described in O'Regan et al. (1975). Mees (1976) developed a spatial simulation model and a procedure that could be used to rank the effectiveness of fixed towers, but OR has not had a significant impact on detection largely, we believe, because of the difficulty of developing aerial detection probability functions and because they largely ignore that the public detects and reports many fires.

Most OR activity has put emphasis on initial attack examples that include the seminal work by Parks (1964) published in *Management Science*. "Initial attack" is used to describe the first efforts to contain a fire and is typically carried out by ground crews (e.g., firefighters) who travel to the fire by truck or by air and attempt to extinguish a fire using pumps and hoses or, in the absence of water, hand tools (e.g., shovels and Pulaskis). Ground crews are often assisted by fixed-wing air tankers that drop water or long-term fire retardants on the fire or helicopters equipped with buckets. Canadair Limited used fire experts' opinions together with a simulation model developed by Stade (1967) to inform the CL-215 air tanker design, the precursor to the CL-415 that is now used to combat wildfires in many countries. Aircraft management (air tankers and transport helicopters) calls for the need to decide upon fleet composition (Martell et al., 1984), home basing (MacLellan and Martell, 1996), and daily deployment (Haight and Fried, 2007). Airtanker systems can be viewed as spatially explicit queuing systems with fire arrival rates that vary throughout the day, service rates that depend upon waiting time, and servers that can and sometimes should be repositioned as the day progresses (e.g., see Islam et al., 2010). In recent years, we have witnessed a growing interest in large fire management that has escaped initial attack, one example of which is Dunn et al. (2017).

Fire behavior is influenced by what forest and wildland fire specialists often describe in simple terms as fuel, weather, and topography. We have witnessed a growing interest in fuel in recent years partly because fire suppression has contributed to an increase in flammable forest fuel loads in some forest regions. Davis (1964) appeared to have been the first to bring OR expertise to bear on fuel management when he had carried out a comprehensive analysis of fuel breaks in a portion of California. Later, Howard et al. (1973) carried out a decision analysis of fire protection alternatives on a 220,000-acre area in the Santa Monica Mountains of Southern California, during which they evaluated many alternatives to reduce costs and losses because of large fires, including improved fire suppression operations, fuel breaks, and fire safety measures around structures.

In recent years, fuel management has grown in importance in part because it has been acknowledged that effective fire suppression has contributed to fuel buildups in some areas (e.g., wildland-urban interface growth). Acuna et al. (2010) incorporated some of the seminal FireSmart forest management practices suggested by Hirsch et al. (2001). More recently, one of us (Weintraub) has been collaborating with wildfire management agencies, forest companies, and colleagues from Chile and the European Community to use the Cell2Fire fire growth model developed by Pais et al. (2021) and develop landscape fuel management plans for flammable landscapes in Chile and Europe.

Landscape-level fuel management calls for computationally challenging spatially explicit stochastic MIP models that have attracted the attention of some specialists (e.g., Bhuiyan et al., 2019). We expect more and more OR specialists to take up the fuel management challenge, but their development and adoption will be slowed by the difficulty in characterizing the impact of fuel treatments on fire behavior and the productivity of suppression forces in treated areas—an important area that has become the center of fire behavior research.

Fig. 5. Harvest operations in northern Sweden done by a mechanized harvester in a remote forest area in darkness. Photo by Mikael Rönnqvist.

5. Tactical and operational harvest planning

Harvest planning essentially selects which harvest areas out of a potential set will be cut during a planning period and considers a given demand for assortment. Each harvest area has a given volume of various assortments. A typical harvest operation in such an area by a mechanized harvester is illustrated in Fig. 5. A business decision on harvesting is based on 0/1 variables and anticipation in terms of production and transportation on continuous variables, often leading to relatively large MIP models. In the 1990s, the solution of such models was limited to smaller sizes; many heuristic solution methods were proposed and used. These methods covered a range of meta-heuristics (e.g., tabu search (TS) and genetic algorithms (GA)) and local search heuristics (e.g., greedy heuristics and various interchange methodologies). In the 2000s, the use of geographical information system (GIS) increased, and road databases enabled more detailed information to be used. Also, models were included in general decision support systems.

5.1. Operational harvest planning: bucking operations

Bucking is sawing felled and debranched trees into sections called logs. Log length is dependent on tree species and the type of final product, which in turn depends on log diameter and quality. Quality is based on knot sizes, sweep, curviness, or taper. Bucking can be done directly at the harvest area where the logs are placed in piles of the same assortment, that is, logs of similar characteristics. Bucking can be done manually by chainsaw operators or by a mechanized harvester machine. The generated piles are then collected by a forwarder machine for further transport to the landing where logging trucks are loaded for further transport to terminals or mills. These operations are illustrated

Fig. 6. A mechanized harvester (left) and a forwarder (right). Photos by Mikael Rönnqvist.

in Fig. 6. In the right part, a harvester performs felling, debranching, and bucking of the tree. In the left part, a forwarder picks up the generated piles of different assortments. Last, bucking can also be done at the landing when full trees are moved by a skidder or a cable system. Alternatively, full trees can be transported to a terminal or sawmill for bucking. In such cases, more sophisticated measurement systems can be used to better optimize bucking or to consider specific demand situations.

Two main bucking processes are involved (Marshall, 2007): buck-to-value and buck-to-demand. The buck-to-value process optimizes the bucking of each tree, whereas the buck-to-demand process optimizes a set of trees against a given demand of logs. The standard approach to solve buck-to-value is to formulate a network model, which essentially solves the longest path problem. By making a suitable discretization of the tree, it is possible to solve this problem efficiently using dynamic programming. Pnevmaticos and Mann's (1972) paper was considered to be the first paper outlining this solution approach. Briggs (1980) later modified the network formulation to be more flexible in terms of how the tree is discretized. Näsberg (1985) developed a Dijkstra-based algorithm that is one of the first implemented into onboard bucking computers in harvesters. In 1985, the forest company Weyerhaeuser won the INFORMS Franz Edelmann Prize for their bucking simulator VISION based on dynamic programming and its raw material cost improvement exceeding US$100 million. The application and experience are described in Lembersky and Chi (1986). Onboard bucking computers collect information from the harvester head and are limited to a two-dimensional tree description. In case of defects, the harvest operator can enforce manual decisions or forced cuts. It is possible to get three-dimensional information for more detailed bucking solutions and integration with the sawing processes at sawmills. There is a vast literature on many breakdown and sawing optimizations, but they are not included in this paper because they are associated with sawmill production. To collect three-dimensional information in the forest, it is possible to use digital calipers. Rönnqvist (1995) described a technical solution for a New Zealand forest company using a dynamic programming model for 3D bucking. This system was used to evaluate team performance by optimizing the bucking at landings using cutting cards or a set of possible log types with detailed information regarding quality restrictions on sweep, knot size, and taper.

In the buck-to-demand process, bucking patterns must be identified to satisfy a specific demand for log types. A first approach to match supply with a demand using bucking patterns was done by Smith and Harrel (1961). Eng et al. (1986) used the classical Gilmore and Gomory (1961) column generation approach to solve the problem. The approach is to solve a coordinating LP with the demand constraints and decisions on how many of each bucking pattern is to be used. It is possible to construct new cutting patterns with dual information. The process is then repeated until no additional cutting pattern is generated. However, Sessions et al. (1989) noted the need to categorize trees into certain classes, limiting practical use. Onboard bucking computers collect diameter information along the tree, and optimization is based on so-called price lists, a matrix of values for every length combination and diameter class. If suitable price values are selected, the bucking process can generate log production in many different classes representing the actual demand. This can be done using a manual process where a set of initial prices are selected. A simulation process is made with a set of measured trees to find the actual production. Prices are adjusted depending on under- and/or over-production. This process is repeated until a satisfactory result is found or a limited number of adjustments are done. Timan 4.0 is a suite of software modules developed by the Forestry Research Institute of Sweden (Skogforsk) to analyze bucking processes and price lists. A modification is to dynamically change the prices as the actual production is known. Sessions et al. (1989) developed a system to adjust prices to find a correct ratio of long logs to short logs. There is no guarantee of optimal solutions, but it is working in practice. All harvester manufacturers implement their own bucking optimization. Standard for Forest Machine Data and Communication (StandForD) is a forest data and communication standard between forest companies and output from the harvester production. StandForD has been coordinated by Skogforsk since the first initiative to establish a standard was taken in 1986–1987. The first standard was decided in 1988. The current version (as of 2023) is called StandForD 2010. Documentation is revised annually. Kemmerer and Labelle (2021) provided a review of how harvester data can be used to improve harvest operations.

5.2. *Tactical harvest planning*

Increasing environmental concerns regarding visual disturbance, habitat fragmentation, and social impacts of harvest activities led to the need to limit harvest area size. This led to the development of so-called adjacency constraints during the 1990s and 2000s, which limited the size when neighboring harvest areas are harvested (see Jones et al., 1991; Murray and Church, 1995; Murray, 1999). The first model type was called unit restricted models and assumed that two neighboring identified areas would exceed a threshold limit (typical limit was 40 hectares). To be more flexible, it is possible to include harvest area design in the model, resulting in the area restriction model. Here, a large set of combined smaller blocks are aggregated into potential harvest areas. Special methods are used to identify the minimum number of constraints needed to formulate the model. Murray et al. (2004) and Goycoolea et al. (2005) proposed methods where all feasible areas were generated *a priori* and solved using commercial MIP solvers. Other environmental needs were to consider the need to have large continuous old-growth patches for wildlife to move freely (Carvajal et al., 2013). Weintraub et al. (2000) described the harvesting situation and implementation of various environmental criteria in Chile and New Zealand.

In the 1990s, Epstein et al. (2006) developed a system to locate machinery and transport logs cut and lying on roads to be transported to mills or other destinations by truck. Road hauling was done by skidders on flat terrain and in towers that pulled up logs in steeper areas. Using information based on GIS maps, the system developed optimal solutions that spatially located machinery and designed roads needed to reach the harvesting areas. The optimization was carried out by a heuristic-based MIP. This system, known as Planex, is still in use by a large firm in Chile.

In the 1990s, harvest models were often integrated with other aspects (this will also be covered in the transportation section). Many extensions have been proposed. One example is found in Richards and Gunn (2000), which includes road construction and where heuristics based on TS is used for the larger model solutions. Another example is found in Epstein et al. (1999b). Here, bucking and harvesting decisions are at times taken jointly, when the best possible cutting units are selected simultaneously with cutting patterns to match a specific demand. The 2000s saw an increase in available data for roads, supply, harvest teams, and demand, resulting in the development of more detailed models that included decisions on which teams were to be allocated to which area beside temporal decisions. One example is found in Karlsson et al. (2004), where the MIP model can be solved using a commercial solver. Heuristics based on depth-first search to generate feasible solutions fast was also proposed due to model complexity. The details in the models increased even more. The model proposed in Bredström et al. (2010) includes also sequencing decisions, that is, team movement between harvest areas and imposes dependency between harvest decisions, as different sequences have different costs. An exact formulation would require constraints using traveling salesman-type subtour elimination constraints. Models would be too large for practical cases; instead, a heuristic approach based on a hierarchical decomposition is used. Here, sequencing costs are approximated in a first phase where all harvest and allocation decisions are made. In a second phase, all sequencing decisions are made within each time period, that is, four seasons in the case study. Models become extremely large for shorter time periods. In the 2010s, companies asked for more detailed harvesting planning. Many enterprise resource planning (ERP) systems used by forest companies included modules where manual harvest planning over the next month(s) was included. Detailed harvest schedules for each team without considering longer-term impacts over a short period lead to suboptimality. Frisk et al. (2016) proposed a heuristic based on hierarchical decomposition. A detailed MIP model with daily time periods is used as a basis. By aggregating time periods to longer anticipation periods in the future, it is possible to reduce model size while keeping business decisions detailed and anticipatory decisions more aggregated.

6. Transportation planning

Transport activities require products to be moved between a supply and demand point (e.g., roundwood, trees, forest residue, wood chips). Transportation can be provided by trucks of different configurations, vessels, and trains. Figure 7 illustrates a typical logging truck size in Sweden. Supply points can take the form of harvest areas in the forest, terminals, or mills, whereas demand points are terminals, harbors, and mills. Two main approaches are taken to plan these activities. The first approach is more aggregated and tactical and considers transports as flows; the second is more detailed and operational and uses specific routes where more details on truck capacity and costs can be modeled. Routing is connected to the general vehicle routing problem (VRP) class. However, forest routing has some specific characteristics: A route is defined by a pick-up at a supply point (e.g., harvest area) and a delivery to a demand point (e.g., mill). In both approaches, multiple time periods and inventory at the supply and demand points can be considered, and a network formulation of nodes represents supply and demand points, and arcs, the possible transportation roads. A

Fig. 7. A Swedish logging truck with a maximum weight of 74 tons and length of 25.25 m. Photo by Mikael Rönnqvist.

recent review and description of the routing and planning system in forestry is found in Audy et al. (2022). Transportation is also integrated with strategic road construction planning. All three levels of planning are covered in the sections below.

6.1. Operational transportation: routing

An early article by Shen and Sessions (1989) introduced a capacitated LP network flow model to solve the daily log truck scheduling problem. The problem is solved using a primal-dual method with the out-of-kilter algorithm. Robinson (1994) also used a network flow formulation for the daily vehicle routing and scheduling problem. In his study, the problem consisted of time windows, multiple origins, destinations, and products, using heterogeneous vehicles. Three solution approaches were presented for the tour generation, including network programming, an explicit tree search enumeration, and a hybrid method of network programming. Developed in the early 1990s, ASICAM (Epstein et al. 1999a) was one of the earliest systems that supported daily truck routing and scheduling decisions. It is based on a simulation model with embedded heuristic decision rules to assign trips among many supply and demand sites and schedule trucks for as many as 300 trucks daily. It is used by many forest companies in Argentina, Brazil, Chile, South Africa, Uruguay, and Venezuela. Rönnqvist and Ryan (1995) considered dispatching for a New Zealand forest company. Two heuristic phases and an optimization phase based on LP relaxation and column generation were used with information updating procedures, enabling problems to be resolved quickly upon new information updates. Rönnqvist et al. (1998) compared two approaches for real-time dispatching problems that dealt with dynamic changes during daily operations.

Routing problems in forestry are often large; exact methods based on MIP formulations were limited to smaller problems. As a result, various heuristic approaches were developed. Often, developing routing forest applications was done in parallel with general VRP problems but adjusted to meet specific forest characteristics. Palmgren et al. (2004) and Rey et al. (2009) presented column generation methods to solve the log truck scheduling problem, where each column indicated a feasible truck route. Models were based on generalized set partitioning models or general column-based MIP models but included heuristics to find quick solutions to the MIP model. Only a limited set of columns were generated for faster solution times.

Gronalt and Hirsch (2007) proposed a TS method to generate a daily truck schedule, where all transportation was provided by full truckloads. Flisberg et al. (2009) also provided an example of using TS that presented a decomposition method. The formulation was flexible, enabling multiple pickups and change of drivers during the daily route. The problem is decomposed into two subproblems with a two-phase solution approach. In the first phase, an LP model is solved to generate destinations between supply and demand nodes, and in the second phase, a TS method is used to find daily routes. Rix et al. (2015) used a column generation method to solve integrated tactical timber transportation and allocation planning, considering the anticipated detailed truck routes and schedules. The problem is formulated as an MIP model with a multiperiod planning horizon that combines the tactical timber transportation with operational logging-truck routing and scheduling components.

More interest was directed to truck queuing and loader synchronization in the 2010s. El Hachemi et al. (2009, 2013, 2015) presented a series of two-phase hybrid methods for related vehicle routing and scheduling problems, each addressing multiple weekly and individual daily VRP coordination. Special attention was given to forest loader and truck arrival synchronization. Kent et al. (2014) proposed an ant colony optimization heuristic to solve a routing problem of delivering timber from forests to sawmills that included queuing. Bordón et al. (2020) presented a hierarchical scheme for a new log transportation problem variant with waiting times at demand and supply points. The original problem was decomposed into two phases. The first phase was based on an MIP that solved the raw material allocation while minimizing transportation costs; the second phase used an MIP to schedule truck arrival to harvest areas and mills while minimizing excessive maximum route duration and waiting times at both locations. Melchiori et al. (2022) proposed an arc-based model with a time grid discretization that simultaneously managed routing and scheduling in the forest supply chain, making it possible to include queuing in planning operations.

6.2. Tactical transportation: flow planning

Many forest management and harvest planning models use transportation as a basic component. The basic model uses decision variables to indicate the flow between supply and demand points, which can be extended with time periods and can include inventory variables. These types of models are used in destination models. Figure 8 illustrates a transportation problem with flows as decision variables. In such a problem, it is often assumed that trucks are driven from supply to demand points loaded and unloaded driving back to the supply point.

An interesting extension is to use so-called backhaul routes. These routes are a typical improvement where the unloaded distance can be reduced by identifying efficient combinations in which a truck makes a new loaded transport between another combination of supply and demand nodes instead of going straight back to the first supply point. This is illustrated in Fig. 9 where two loaded

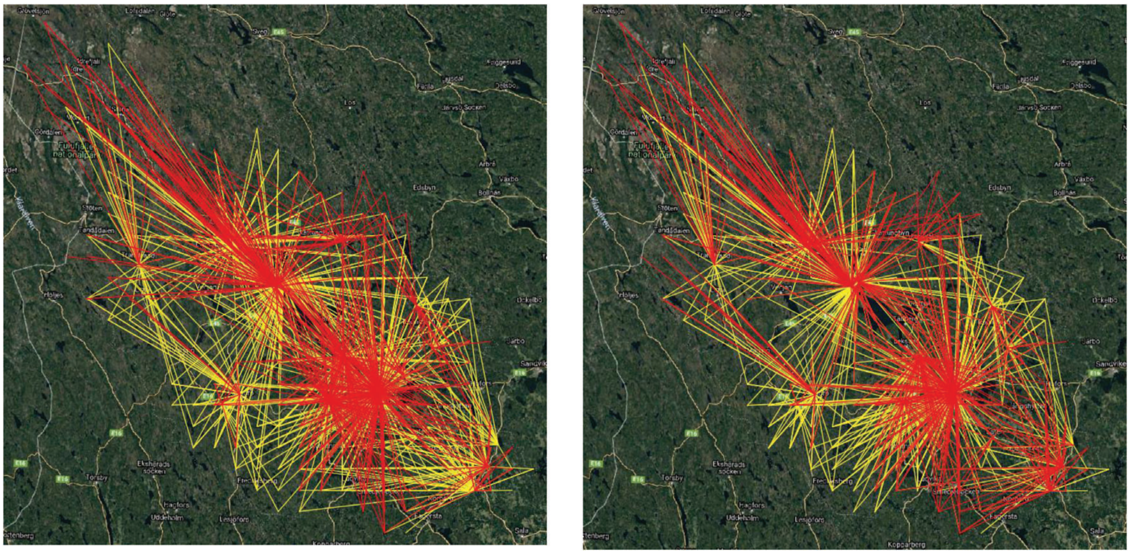

Fig. 8. Illustration of the flows between a set of supply and harvest areas for two collaborating companies with actual flows (left) and optimized flows (right).

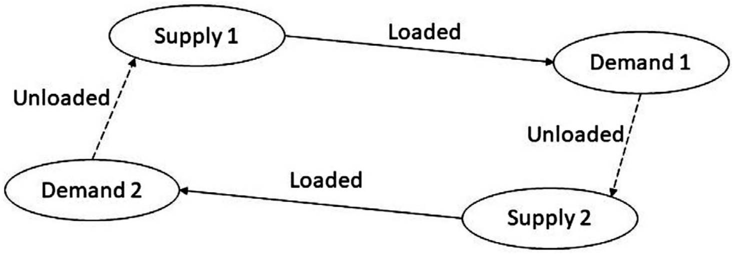

Fig. 9. An example of a backhaul route for a single truck where the solid lines represent the loaded transports and the dotted lines unloaded transports.

transports are combined. The main idea is to find combinations of two (or more) transports such that the unloaded distance can be reduced as is the case in the figure where the combined dotted lines are shorter than the combined solid lines. Backhaul routes dramatically increase LP model size; column generation methods must be used (see Carlsson and Rönnqvist, 2007). During the 2000s, Forsberg et al. (2005) developed and presented an integrated transportation planning system called Flowopt at Skogforsk. The system considered truck and train transportation of multiple assortments, from many harvesting areas to various industries where backhauling was also included. This system won the EURO Excellence in Practice Award in 2012. Correct distances are crucial in destination planning (Rönnqvist, 2012). The Calibrated Route System (Rönnqvist et al., 2017) is a standardized system used for more than 80% of all about two million transports in Sweden. The system won the INFORMS Daniel Wagner Prize in 2015. Many flow planning systems have been implemented. For example, the Flowopt system has now matured to a commercial system and is used by many large-scale forest companies in Sweden. Similar models are also used in, for example, forest biomass transports for local energy production (Gunnarsson et al., 2004).

6.3. Strategic transportation: network design

Forest road design is one of the most typical network problems in forestry. These forestry studies often include transportation and harvesting decisions to anticipate business decisions about road construction. Roads are required to harvest and reach the harvest areas. In the 1970s, harvesting and road-building plans were determined separately. Network design models are formulated as MIP models with an underlying network structure that often cover multiple time periods, which can be several years. Because such models are hard to solve, a variety of heuristic approaches and specific application-oriented models have been developed. Kazama et al. (2021) reviewed articles between 2009 and 2019, to examine the methods, techniques, and tools used in forest road planning.

In typical U.S. Forest Service areas, road construction represents approximately 40% of operational costs. Sullivan (1973) very early demonstrated that significantly increased costs were the result of not integrating both decisions. One of the first models was presented in Weintraub and Navon (1976). This model addressed harvesting, transportation, and forest road construction. Road construction must follow a certain sequence that makes the model more complex. A similar model was presented in Kirby et al. (1986). Many methods were proposed thereafter to strengthen MIP formulations by adding various valid inequalities (see Andalaft et al., 2003). Cea and Jofre (2000) proposed a two-level model that coordinated long-term planning with tactical planning, including harvesting and road construction with various standards. Due to model size and the capacity of commercial MIP solvers, only smaller case studies could be solved. Weintraub et al. (1994) proposed heuristic solution methods based on fixing relaxed binary variables to solve larger instances. Many models included additional decisions. For example, Weintraub et al. (1995) extended to also include 0/1 variables for land management. Epstein et al. (2006) integrated road construction with decisions on machine location, and Silva et al. (2010) integrated environmental protection into the model.

The use of public road databases with detailed road information became more available in 2000. Karlsson et al. (2004) studied the network design problem with road upgrading. For example, a road can be upgraded to carry loads during the thawing period. The article used straightforward network formulations. However, these formulations suffer a few disadvantages, especially when a network of many roads is not used for upgrading. In Henningsson et al. (2007), the model was reformulated to a path formulation, making it possible to solve larger problems. Flisberg et al. (2014) integrated long-term harvest planning with road upgrade investments. The article proposed a system that has since been used in multiple investment analyses for forest companies in Sweden.

In the 2010s, many models included uncertainty. Palma and Nelson (2014) presented an MIP formulation for road construction and harvesting scheduling problems, using robust optimization to deal with the uncertainty of timber demand. Álvarez-Miranda et al. (2018) presented a multiobjective stochastic model for sustainable forest decision making under uncertainty, considering multiple objectives such as maximizing carbon sequestration, minimizing land erosion objectives, and including uncertainty in the form of stochastic variables such as demand and price. Additionally, models have been developed to consider other environmental considerations. For example, Yemshanov et al. (2022) explored trade-offs between forest planning, network design, and wildlife corridor preservation. Consequently, larger problems with more details can be solved, as MIP solvers have improved. However, models with strong LP relaxation still need to be formulated. Mesquita et al. (2022) proposed models to support MIP solvers, where the LP relaxation is stronger than standard models.

Harvest and forwarding operation planning on a harvest area with cut-to-length operations integrates many aspects of transportation, including routing and network design but with a much shorter planning horizon. Before the 2010s, these operations were planned and operated manually in two main phases. In the first phase, a planner marks the main extraction trails to avoid soil damage, indicates where temporary bridges are built, and avoids damage to cultural sites. The harvester follows the extraction trails and produces log piles logs, whereas the forwarder gathers all piles and moves them to the landing beside the forest road, where logging trucks transport the logs to demand points. In the second phase, the routing of the forwarder is decided. Essentially, the forwarder solves a large-scale VRP where considerations for co-loading assortments are difficult decisions. Co-loading leads to increased time for loading and sorting at the loading point. It is possible to formulate network design models (Flisberg et al., 2021a, 2021b) for extraction trail design and complex forwarder routing with co-loading considerations as a result of LiDAR and harvester production files (Hansson et al., 2022). It is also possible to continually develop full automation with such decision support tools.

7. Value chain management

The emergence of value chain management or supply chain management dates back to the 1990s and was primarily driven by larger integrated manufacturing industries. During this time, ERP systems were developed to facilitate improved coordination and advanced planning. The forest supply chain (SC) or value chain (VC) is made up of various industrially integrated VCs, including pulp and paper mills, lumber production, biorefineries, and energy production. In addition to other natural resource VCs, the forest VC is noted for unique characteristics. A number of public and private organizations, such as small- and large-scale companies, governments, Indigenous communities, hunters, and tourist representatives, are part of the forest VC. These organizations are influenced by socioeconomic, technological, and environmental forces, laying out a set of objectives that may often conflict with each other despite sharing common goals. The forest VC processes are, in general, divergent, that is, the number of products increases through the chain. In contrast, manufacturing industries are convergent, that is, the number of products is large at first but eventually gets reduced in the chain as products are assembled into more complex parts. This divergent behavior poses challenges in balancing supply and demand. Planners generally prefer a "push" approach, mainly because they encounter difficulties with divergent flows and need to adapt to changing information. Unfortunately, there are limited tools available in practice to support advanced planning in divergent process industries. Consequently, coordination between stakeholders is often conducted on an *ad hoc* basis and implemented through contractual terms that rarely engage more than one additional partner at a time. VCs require extensive amounts of resources, processes, and business data. These data are sourced from various locations and are often characterized by a high degree of uncertainty due to the inherent difficulty in estimating the volume and quality of natural resources. Additionally, transportation activities using trucks, trains, and vessels are typically vast and spread over large geographical areas.

Carlsson and Rönnqvist (2005) described several models used for integrated planning in a vertically integrated forest company in Sweden. The integration provides opportunities for cost saving, increased sales, and increased information sharing and transparency within the company. Bredström et al. (2004) proposed an integrated production, inventory, and transportation model to ensure coordination between the forest regions and three pulp mills for a large forest association in Sweden. Unlike sequential planning, the integrated model not only finds improved solutions but also shows a common misunderstanding of what is an efficient plan. The paper won the EURO Excellence in Practice Award in 2001. This is later followed up by using robust optimization in Carlsson et al. (2014). Troncoso et al. (2015) developed a VC model for an integrated forest company in Chile. Decisions included harvesting, bucking, transportation, production, and sales and covered business decisions for the next five years and anticipation for a full forest rotation in approximately 25 years. Model results showed significant improvement over traditional decoupled planning in each planning unit.

The primary VC management objective is to integrate planning units and facilitate information sharing across all business units. Collaboration and coordination are powerful tools for managing value chains effectively (Cloutier et al., 2020). Though the terms "collaboration," "coordination," and "cooperation" are often used interchangeably, they describe distinct concepts. A commonly accepted definition of collaboration is "an intentional cooperative action between two or more entities that exchange or share resources, with the goal of making decisions or realizing activities that will generate shared advantages or losses" (Audy et al., 2012). Horizontal collaboration involves organizations engaging in joint planning at the same VC level. Collaborative efforts in transportation and routing have the potential to significantly reduce costs and fuel consumption (Frisk et al., 2010). For example, a company may traditionally rely on multiple transporters who plan their routes independently. If they agree to a joint planning approach, transport resources can be utilized more effectively, matching supply and demand more efficiently and reducing fuel consumption. A simple example of collaboration is two forest companies engaging in wood bartering, where one company supply can satisfy the demand of the other, resulting in better flow destinations and shorter average distances. Guajardo and Rönnqvist (2016) provide a review of cost allocation methods. Despite the availability of proportional sharing principles, Shapley values, and game theoretical models to provide cost allocation models, Basso et al. (2019) showed that very few collaborations are put into practice due to reasons such as lack of trust, sensitive information sharing, leadership structure, and cultural behavior. Standardization is a crucial consideration to support collaboration; sharing benefits is equally important.

In Canada, the *FORAC research consortium* and *Value Chain Optimization Network* were early initiatives that explored forest value chains in close collaboration with forest companies. The key aspect of needing tools was examined to better understand the complex nature of the value chain. Together with other universities, a suite of freely available online educational tools was developed to support training students and professionals. The use of these tools was described in Fjeld et al. (2014). The transportation game was one example of the developed tools (Abasian et al., 2020); this game provided an understanding of hierarchical planning, where a set of decoupled problems were solved and compared to fully integrated planning. The wood supply game (D'Amours et al., 2017) describes an adaptation of the well-known beer game for divergent value chains. This game is also used in an annual international competition on how to manage uncertainty and control in a value chain.

8. Future challenges for OR specialists

If we stand back and reflect on how the use of OR has evolved in the last five decades, we can see that there have been major shifts, both in the problems that have been at the core of forest management planning as well as the methodologies and technologies used to resolve these problems. As shown in Fig. 2 (timeline), the focus of forest management planning evolved from simple harvest planning to, for example, the need to pay more attention to environmental issues and to consider the possibility that significant events (e.g., fires) might occur, and when necessary, to replan after they have occurred. The need to solve these problems led to the use of commercial LP and MIP codes, the use of sophisticated MIP and heuristic algorithms to develop complex methods for dealing with uncertainty, artificial intelligence, and the use of satellite and LiDAR imagery.

What do those observations suggest we might do to plan for the future? Experience tells us it is very difficult to predict future events and their potential impact on forests and their management. Had we been asked in the year 2000, to predict how forests would be managed in 2025, we doubt we would have been able to do so very well. Take, for example, the impact of fire on forests, communities in and near forested areas and people that live and work in such communities. Although many climatologists and wildfire scientists predicted climate change would have a significant impact on forests many years ago (e.g., Wotton and Flannigan, 1993), we as a society, have only recently come to recognize that our wildfire regimes have been very significantly impacted by climate change and that the threat they pose will not diminish anytime soon—a growing challenge that we anticipate will garner the attention of more OR specialists than has been the case in the past.

Rönnqvist et al. (2015) outlined a set of 33 open OR problems in forestry. Those problems covered all of the areas touched on in this paper, and it is interesting, 8 years later, to reflect upon their status. Papers that addressed the need for integrated harvest scheduling, bucking, sorting and transportation decisions have been published, but the need for exact algorithms to solve large routing problems remains an important open problem. Another important area of unsolved problems is—how best to coordinate the collaboration on transportation logistics, of competing stakeholders. Basso et al. (2019) showed what is possible, but also what important barriers remain. The problem of using exact algorithms to solve large-scale problems that include harvesting with adjacency and other environmental constraints, road building, and transportation remains open, despite large increases in computer capacity. The development and implementation of models that address uncertainty in forest growth, future markets, and social, economic and ecological objectives remain challenging. We believe that many new forestry-related challenges will emerge and pose important challenges for OR in the future. We have grouped some of those we anticipate might emerge under the following themes: climate change and carbon management, biodiversity and conservation, automation and data quality.

8.1. Climate change and carbon management

Climate change will continue to challenge forest management, and we believe forest managers and the forest industry can play an important role because forests and the use of forest products can help sequester carbon and serve as a source of non-fossil fuel. Forests that were once viewed primarily as a source of industrial fiber are now largely viewed by many, as a resource that is to be managed not only as a continued source of industrial fiber but also, to achieve many other objectives including those associated with water management, wildlife conservation, recreation, and carbon sequestration. Media images of wildfires bearing down on and destroying communities, forcing mass evacuations, and killing some residents are searing reminders that climate change has been taking place and has probably convinced many doubters and climate change deniers that climate change is indeed “real.”

Although forests have clearly “suffered” from climate change, some forests might be managed to mitigate its impact. Consider, for example, that forests store large amounts of carbon (Pan et al., 2011). These amounts have been and continue to be released into the atmosphere through fires and traditional forest harvesting methods and land clearing to support agriculture and other human land uses. But as Carle et al. (2021) illustrated, some forests provide opportunities to sequester carbon. Of course, developing and implementing carbon sequestration strategies will be complicated by considerable uncertainty, some of which are explored by Yousefpour et al. (2012), but we believe that operational researchers can and will play key roles in strategy development and implementation.

Climate change also poses several challenges for forest operations and transportation. Extreme weather events such as drought, floods and wildfires, can disrupt forest operations and transportation, resulting in increased costs and reduced efficiency. Changing weather patterns can affect forest road stability of forest roads and load-bearing capacities. These challenges highlight the need for improved climate change adaptation strategies in forest operations and transportation planning models.

8.2. Biodiversity and conservation

As noted earlier, non-timber objectives have grown in importance in forest management over the past 50 years, and many authors have developed OR models to explore how timber production might best take place on land that must be managed to achieve wildlife conservation objectives. Consider, for example, woodland caribou in Canada’s boreal forest region. Industrial timber production and other human activities have had—and continue to have—a significant detrimental impact on woodland caribou populations as documented in Environment and Climate Change Canada (2020). Consequently, it is increasingly crucial to incorporate caribou conservation concerns in forest management planning across Canada. However, such planning calls for spatial models that account for many factors, one of which is that caribou have to move between patches of desirable habitat along paths that are not disturbed by roads, harvesting, and other human activities. Martin et al. (2017) illustrated how OR might contribute to helping resolve such problems by incorporating a LP model in a re-planning framework to minimize the detrimental impact of achieving specified timber production targets on woodland caribou habitat.

Another challenge lies in balancing conflicting objectives, such as social, economic, and ecological concerns. For example, the increased mechanization of harvesting operations can lead to increased productivity but may also negatively impact forest biodiversity, soil health, and water quality. Multiple stakeholders might have different objectives, and coordinating or enabling collaboration among stakeholders can be difficult, particularly when they have conflicting preferences. For example, the objectives of forest managers that seek to optimize the production of timber for

Fig. 10. Aerial photo of continuous cover harvesting where the individual open cut areas are less than 0.25 hectares. Photo by Mikael Rönnqvist.

industrial purposes usually differ very significantly from those of environmental conservation groups, and such differences make it difficult to find common ground and work toward shared goals. We believe OR can help inform the resolution of such problems. Declines in biodiversity have stimulated discussion of the merits of traditional harvesting operations. There are more discussions, for example, of alternative harvesting forms, including so-called continuous cover harvesting. The main idea is to harvest only a limited area to avoid the impact on biodiversity, see Fig. 10. Such new harvesting strategies may be beneficial for biodiversity but provide new challenges for logistics activities. New harvesting methods will require new logistics approaches, and we believe OR approaches can support these transformative activities.

8.3. Automation and data quality

The lack of experienced staff in remote and difficult working conditions is stimulating the need for increased levels of automation. The use of automation in forestry poses numerous challenges in a hierarchical structure. For example, in harvesting operations, all harvester routes must be initially established, and tracking must be detailed to control the machine locally to avoid obstacles such as larger rocks or sensitive, wet soil. These levels require different types of software and data details to enable automation. The availability of big data in various databases has made it possible to solve exciting new problems. However, databases lacking strict quality protocols or standards may contain low-quality or erroneous data. For example, forest managers may use remote sensing data to estimate tree height, species composition, and volume, but these data may be subject to errors, resulting in suboptimal management decisions. Drought and fires can lead to significant forest structure changes and composition, making it difficult to accurately predict future growth and yield.

Thus, it is crucial to develop models and methods that can classify and manage data quality in the optimization models. This stresses the need for efficient models and stochastic optimization models.

In early model development in the 1970s and 1980s, industrial data for large model formulations were often lacking, and LP and MIP solver capacity limited the size of problems that could be solved. However, significant commercial solver developments between 1980 and 2000 and increased laptop speed and memory capacity eventually made it possible to solve larger problems. Additionally, increased data accessibility in various large open databases between 2000 and 2020, such as public road databases and LiDAR data, enabled larger model formulations and solutions. In many cases, however, the time required for modeling languages to produce optimization models that can be passed to solvers is much longer than the actual solver solution time. Developing preprocessing or new model structures to reduce conversion times presents a new challenge.

9. Concluding remarks

OR has played an important role in forestry over the past 70 years, and we expect it will play an even more important role in forestry in the coming years. We have been very fortunate to have had an opportunity to be involved, and our hope is that the publication of this paper in the OR literature will bring forestry to the attention of others in the OR community and encourage more of our OR colleagues to become actively involved in and to tackle some of the many important forestry-related challenges that remain as well as others that will emerge as we move forward.

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