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Operations Research challenges in forestry: 33 open problems

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Abstract Forestry has contributed many problems to the Operations Research (OR) community. At the same time, OR has developed many models and solution methods for use in forestry. In this article, we describe the current status of research on the application of OR methods to forestry and a number of research challenges or open questions that we believe will be of interest to both researchers and practitioners. The areas covered include strategic, tactical and operational planning, fire management, conservation and the use of OR to address environmental concerns. The paper also considers more general methodological areas that are important to forestry including uncertainty, multiple objectives and hierarchical planning.

Keywords Forestry · OR challenges · Transportation · Harvesting · Environment · Forest management · Fire management · Operations research · Strategic · Tactical · Operational

1 Introduction

The forest industry is very important from both regional and national perspectives in many countries. It constitutes a large proportion of the net exports in, for example, Canada, Chile,

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Finland, New Zealand and Sweden. Forests provide a wide variety of products such as paper, wrappings, building materials and furniture. At the same time, they also provide many services such as recreation, wildlife habitat, clean water, scenic amenities, and carbon storage. Planning problems in forestry range from land-use, regeneration, road building, harvesting, transportation, to production at saw-, pulp-, paper-mills and heating plants. In each of these cases, careful attention must be paid to social and environmental issues as well as company specific restrictions and goals. There are many differences in practice, organization and ownership between countries. In some countries, a company may control almost the entire wood-flow or supply chain whereas in others, there are many companies involved on a specific portion of the chain. This of course also has an effect on how planning is performed and the efficiency of each company. There are also mixes of private and state-owned companies with different objectives and government regulations that differ significantly between countries. There may also be special consideration and support for local communities in terms of the current employment situation. Some countries have regulations that call, for example, for harvest plans to be approved by local authorities. Others have less stringent rules on operations in, for example, plantation forests. Another difference is that growth rates vary from region to region and there may be a five-fold difference between, for example, plantations in Chile and natural forests in Russia. Because of this, the rotation time between planting and harvesting may vary from about 8–10 years to 80–200 (or more) years.

The forestry community has been a very active user of Operations Research (OR) models since the 60's, with the introduction of Linear Programming (LP) models to support long-range harvesting and regeneration decision-making beginning with Timber RAM, which was developed by the US Forest Service (Navon 1971). OR has been applied across a broad range of decision-making problems including strategic long-range planning which deals with sustainable long-range aggregate silvicultural policies and non-declining production, tactical problems which deal with the spatial sequencing of harvest areas, road building and very importantly in the last few decades, environmental regulations directed at protecting wildlife, water and soil quality, carbon sequestration, and promoting biological diversity and sustainability. Proxy measures related to spatial characteristics of harvesting activities have been developed to address such concerns. At the operational level, typical decisions involve harvesting, bucking and the distribution of logs to satisfy different demands, transportation from the forest to terminals and customers, and location of machinery and construction of secondary access roads. In order to assure consistency in decisions, viewing the interaction in a hierarchical fashion is important. Also, trying to integrate the forest supply chain from the harvesting of trees to final products has been another issue. Finally, there are challenges that emerge from the nature of forest problems and the need to address uncertainties in future prices, tree growth and natural disturbances such as fires and pests, and to consider multiple attributes such as timber production, recreation, social and environmental values.

The diversity of decision problems and size of planning tasks have increased significantly in recent years. More information has led to larger models, and more restrictions have led to more complex constraints. The impact of OR in forestry has been acknowledged in the form of prestigious awards such as the INFORMS Franz Edelmann Award (see Epstein et al. 1999) and an survey on how OR has been used can be found in D'Amours et al. (2008). A detailed description of various management problems in forestry can be found in Weintraub et al. (2007) and in a recent book edited by Borges et al. (2014).

The aim of this paper is to present the general problems, the research knowledge in these diverse problem areas, and to discuss where we believe new challenges or open problems exist. Our focus is on the woodlands portion of the forest value chain. The challenges we describe can be expressed at different levels:

- How to define, analyze and understand different problems. What is the essence of these problems? How can we find relevant data for them?
- How to incorporate reality into representative models. What are acceptable approximations that still reflect the basic reality in a reasonable way?
- How to develop representative models that are solvable, and such that users feel their solutions will be of help in their decision making.
- For many problems, determining adequate solution algorithms which lead to at least good approximate solutions with reasonable computer effort is difficult. In some cases, heuristic solutions are the best available approach. In other cases, exact or nearly exact solutions can be obtained in acceptable computation times.

We believe our description of the challenges or open problems presented below will be of interest for different reasons. Some open problems are theoretical, related primarily to methodological research along the four lines of enquiry outlined above. Other challenges and questions are related to the application of concepts, methodologies, models and algorithms to actually solve real problems and may be of more interest to practitioners. In the following sections we present what we believe are the main areas into which the forest value chain theme can be classified, and the current state of the art in terms of what we consider to be important open problems to be tackled by researchers and forest practitioners. We are of course, aware that there are many other important and interesting areas and questions that we have not included.

2 Operational harvesting

Operational harvesting relates to all activities associated to harvesting forests (Epstein et al. 2007a). This is a short-term decision process that involves operations starting with cutting the trees to deliver logs to primary and secondary customer destinations. Transportation is part of the operational decisions, but given its importance it is reviewed in a separate section, *Transportation and Routing*. The operational supply chain, integrating all operational activities from forest to markets is also presented in another section, *Value Chain Management*.

Harvesting operations involve several major decision problems. The first one is the direct felling and subsequent bucking of trees. This can be a highly mechanized operation with special harvesters or a manual operation involving chain saws. The technique used depends on the geographical conditions and tree size. The second problem is the sequencing of stands to harvest and which crew and equipment to use. A third problem is the use of harvesting machinery to bring logs to load into trucks, and the secondary roads that need to be built for access. Time horizon here goes from a day to a few months. The log bucking may take place either directly at harvest points or at saw mills where more sophisticated equipment can be used. These decisions can consider deciding how to buck each individual tree so as to make it most valuable, given the tree characteristics, orders and prices for specific products, which are generally defined by length, diameter and quality (lack of defects). The models in this area involve a combination of LP, integer programming (IP) and mixed integer programming (MIP) models.

At another decision level, models have considered forest-wide operations, where decisions on forest operations are made to satisfy demand. The basic problem here is to match standing timber with orders specifying length, diameter and quality. Linear programming has been widely proposed to solve these problems (Martell et al. 1998). Epstein et al. (1999) developed a system used by several forest companies in Chile which supports decisions on which stands to harvest each week, how to buck trees and send products to different destinations to satisfy demands. The system is based on an LP with column generation for the bucking patterns. Incorporating crew scheduling has also been proposed by Bredström et al. (2010). These problems have essentially been modeled and solved with success.

Part of operational decisions is the use of machinery for harvesting. This machinery is usually composed of skidders or forwarders for flat terrains and cable logging or towers for steep areas. Towers are located on the top of steep areas and logs are brought up with cables. In some cases, cable logging can be carried downhill, but this is more complicated due to the dangers of hauling logs down due to gravity. Once a tower is positioned, a cable is extended downwards in a given direction and logs near the cable are attached to it and brought up. The cable length goes from 300 to 1000 m, but can be extended of course as long as it does not encounter an obstacle, such as a stream or an abrupt change in slope. Helicopters, barges and even animal traction are also used but not often.

The main decisions can be described as follows. Given an area of appoximately 400 ha to be harvested in the next few months, how should the harvesting machinery be located? Which areas should be harvested through skidders, where should towers be located and which access roads should be built? Roads are needed in skidder areas, given their slow speed; it is usually not economical to use skidders farther than 300 m from a road site, where logs can be loaded into trucks at roadside. Also, roads are needed at tower positions to load logs brought in through cables. Several software packages have been developed to support these decisions. PLANS was developed as a support tool for the US Forest Service which, based on Geographical Information System (GIS) information after the user determined the positions of harvesting machinery, defined the loads harvested by each machine, access roads, timber volumes and cable logging technical details.

The problem of including machine location in the decision process was developed by Epstein et al. (2006). This system, PLANEX, is based on GIS information, a visual interactive interface and a heuristic algorithm to determine best locations of machinery, access roads, and timber harvested. This system is used by several forest firms in Chile. Solving this problem in an exact formulation is very complex. The problem can be viewed as a combination of a plant location problem, where the harvesting machinery plays the role of plants and the timber cells play the role of customers, and a fixed charge network flow problem to account for the road building plus hauling. This leads us to our first open problem.

Open Problem 1 *How can we solve the equipment location problem in an exact formulation for large-scale instances?*

While modeling integration of harvesting and transportation activities has been proposed for longer range periods, up to 12 months in Sweden, no such efforts have been made for short integration. In daily or weekly scheduling of activities, there is a link between harvesting and transportation activities which, so far, have been planned sequentially. Once the harvesting decisions have been taken, the transportation system receives them as data to schedule trucks. There is an advantage in making these decisions integrated. So far, there appears to be no publication showing a system which integrates daily or weekly harvesting and transportation decisions.

Open Problem 2 *How can we model and solve the scheduling of jointly detailed daily or weekly harvesting and transportation decisions?*

Environmental issues are also of importance in harvesting. Harvesting operations cause damage and there are many certification rules that describe what is and is not allowed.

Harvesting with heavy equipment on fragile soils causes erosion. Also, building roads on steep slopes harms the soil. Harvesting near water ways causes sedimentation. Measures to prevent these damages include using cable logging on fragile soils, leaving riparian strips of up to 100 m on rivers where no harvesting is carried out, and building fewer roads and in a more appropriate location. Models have been proposed which incorporate these measures into the planning of harvesting, in such a way as to minimize the associated loss of timber harvested and operational costs (Caro et al. 2009). However, usually there is no gauging of the reduction in environmental damage obtained through these measures.

Open Problem 3 *How can we establish the environmental impacts of different operational harvesting practices and define models to avoid any negative impact?*

Although timber can be sorted in many ways in the forest, forest managers tend to reduce the number of assortments in order to keep the operating costs low. However, considering the many potential usages of timber products (e.g. sawmills, pulp mills, heating plants) and the need to better match supply with demand, the optimal number of assortment is still to be defined through a global analysis of the wood supply chain. In terms of modeling, Carlgren et al. (2006) have proposed a model defining the sorting strategies in order to match pulp mill demands. The model could be extended to integrate the impact of the sorting strategies on process efficiency at the mills; knowing that timber with specific fibre characteristics can be processed in different ways and potentially provide higher value products. The modeling of these alternatives processes could be done easily. However, the definition of the model parameters (sorting costs, process efficiencies in terms of fibre characteristics, linkage between fibre characteristics, process and end-product characteristics) still remains a challenge.

Open Problem 4 *How can we synchronize operational sorting, harvesting and transportation decisions for large-sized forest problems?*

In harvest operations with on-board computers for bucking, price lists are used to direct the bucking into a certain combination of diameter and length class. However, the process of managing such internal prices over several harvest areas has not received attention in the literature.

Open Problem 5 *How can we use pricing as a coordination mechanism for forest operations?*

3 Transportation and routing

Transportation is an important part of the logistics planning in forestry, and it often represents more than one-third of the total cost. Several modes of transportation are used; truck, train, ship and water. In addition, wood chips and bark are carried from saw mills to pulp mills, paper mills and heating plants. Different types of trucks are used depending on the type of raw material and operational conditions. The mills are dependent on continuous deliveries throughout the year. The transportation planning is often integrated with forest operations including road building/upgrading/maintenance and harvesting as discussed above. The transporters may also collaborate in larger transport associations. These associations take on work negotiated with the forest companies and distribute the work among their members. Forest companies work together with both small and large associations and, in some cases, operate their own fleet of trucks.

How the transportation planning is done, by whom and to what level of detail varies significantly. One case would be when a forest company organizes and makes central planning for one fleet of trucks. These trucks may belong to one or several independent transporters. A second case would be when one large transport company organizes the transportation for several forest companies or organizations. A third and more decentralized case would be when several transportation managers, each responsible for a region, provide target quota for the number of loads that should be carried from specified roadsides to different mills. The transporters may then organize the work independently from other transporters and just keep in contact with harvesting personnel in order to ensure that there is enough wood at the landing ready for haulage. To support planners, the use of decision support systems (DSS) including GIS and road databases has increased. Also, mobile communication to keep information accurate is also increasing.

There are different planning horizons for the planning process. The main ones are destination planning which uses flows with weekly or monthly periods, routing which determines daily schedules for individual trucks, and strategic planning which uses one or several years as the planning period. The latter is typically concerned with the location of terminals, and partial production and sorting sites located close to or in the forest.

The destination problem is generally solved using a monthly planning period. The basis is weekly or monthly quotas agreed on between a forest company and transporters. The main decisions are to decide which log piles or volumes at harvest areas should be transported to which industries. These problems are often formulated with LP models and are relatively easy to solve. In its most simple version, the variables represent the flow from supply point i to demand point j are used together with constraints on supply and demand and where the objective is to minimize total costs. This can easily be extended with, for example, several products, multiple time periods, transport capacities and storage locations and capacities. The destination planning is often done centrally by a forest company with delivery responsibilities for several industries. Once a destination plan has been found, transport orders are distributed to a number of transporters.

The drawback with a standard transportation model with direct flows is that backhaulage tours or return flows are not included and these provide substantial savings. The reason for this is that the classical model only considers transportation from supply to demand nodes. This assumes that the trucks that carry out the work go back and forward between these nodes as many times as there is enough supply. In practice, this provides an efficiency of just 50 % and by introducing backhaul tours the model resembles more practical routing models. The drawback is that the model requires a large number of backhaul tours, making the model very large. To include backhaul flows in the model dramatically increases the number of variables. Hence, special methods like column generation needs to be used (Carlsson and Rönnqvist 2007). These methods have been used in different planning systems (see e.g., FlowOpt described in Forsberg et al. 2005).

There is also increasing work to deal with horizontal collaboration between organizations and companies (Frisk et al. 2010). In such collaborations several entities can make joint transportation planning in order to improve the overall performance. However, it is also necessary to agree on how the increased profits and decreased costs should be shared in a fair and agreed manner. Furthermore, as not all organizations want to share their sensitive information such as agreements, orders and customers, a mechanism needs to be put in place where this information is not shared among the participating organizations. Some initial generalizations can be found in Audy et al. (2012), but there is need for more work to put these collaboration schemes to practice.

Open Problem 6 *How can we model and propose efficient sharing principles for practical collaboration in transportation?*

The routing problem for logging trucks has some particular aspects that make it different from a standard Vehicle Routing Problem (VRP) with time windows. It is a pick-up and delivery problem and there are generally more supply volumes than actual demand volumes. This means that a truck will visit the same location several times. Typically, supplies can be transported to several demands providing the correctness of the products. The demand typically ranges over several days, but with lower and upper limits for each day. This implies integration between days or time periods and the problem becomes a multi-period problem. Each truck has a given home base and working hours. Most trucks change drivers at least once during the day at a specified change-over location. Trucks may be equipped with their own cranes or require the presence of a loader for loading and unloading. Also, some piles may be very small and several pick-ups are necessary to load a full truck.

ASICAM (Weintraub et al. 1996), a DSS for logging trucks, received the Franz Edelman Award in 1998. This DSS is currently used by several forest companies in Chile and other South American countries. It exploits a simulation-based heuristic to produce a one-day schedule. The system, RuttOpt (Andersson et al. 2008), establishes detailed routes for several days and integrates a GIS with a road database, using a combination of tabu search for the routing part and an LP model for the destination part. Even if there are many approaches and methods developed for the forest routing problem, there is no exact formulation that has been solved and used in practice for industrial instances.

Open Problem 7 *How can we model and solve an exact formulation of the forestry VRP problem?*

Dispatching or solving the problem in real-time involves determining routes (or partial routes) continuously during the day, taking real-time events (e.g., queuing, bad weather, truck breakdowns) into account. Rönnqvist and Ryan (1995) have described a heuristic solution method for dispatching, which finds solutions for a fleet of trucks within a few seconds by recursively solving a column-based model whenever data changes occur. As technology has improved, decisions are being made in real-time. This involves communications between trucks, GPS location of trucks, loaders and decision centres in real-time, possibly via satellites or special radio systems. Models and methods dealing with continuously changing data and events deal with new challenges.

Open Problem 8 *How can we develop models and methods of the forestry VRP dealing with real-time planning including queuing at loading and unloading points?*

A problem with VRP planning is that queuing at mill entries or self-loaders is not considered. The reason behind this is that routes are treated independent of each other. To deal with this, synchronization constraints must be included. There have been a number of heuristic approaches (Marques et al. 2014), but there is a lack of working systems that ensures full consideration.

Open Problem 9 *How can we develop models and methods for the forestry VRP that deal with synchronization of trucks and loaders?*

4 Tactical planning

Tactical planning serves as a bridge between the long-term strategic level and the detailed operational planning level which has a direct influence on actual operations (D'Amours et al. 2008). Tactical planning must ensure that subsequent operational decisions are not sub-optimized due to a shorter planning horizon, but rather that the direction which has been set out in the strategic plan is followed. In forestry there are many decisions to be taken at the tactical level. They relate to: defining the sourcing plan for each of the mills (log class), the harvesting aggregated planning, route definition and transshipment yard location and planning, allocation of harvesting and transportation equipment to cutting blocs, allocation of product/bloc to mills, sorting strategies, yard layout design, yard management policies, etc. The planning horizon is normally a year and the planning period could be weeks or months. The scope of the modeling typically integrates harvesting with transportation.

In planning problems dealing with production/distribution issues, tactical planning normally addresses the allocation rules that define which unit or group of units is responsible for executing the different supply chain activities or what resources or group of resources will be used. It also sets the rules in terms of production/distribution lead times, lot sizing and inventory policies.

Tactical planning should also ensure that the subsequent operational planning conforms to the directives established during the strategic planning stage, even though the planning horizon is much shorter. Other typical tactical decisions concern allocating customers to mills and defining the necessary distribution capacity. The advanced planning required for distribution depends on the transportation mode. For example, ship and rail transportation typically need to be planned earlier than truck transportation.

One of the important challenges of tactical planning relates to the fact that often the business units considered in the planning are owned by different owners which limits how much can be integrated into the models. For example, in one instance, a forest can be owned by government and allocated to different companies. For example, this is a common case in Canada. Then in another instance, a forest can be privately owned and timber sold on the market to the company offering the best prices, which is common practice in Scandinavian countries. Another example is outsourcing the execution of the prescriptions to entrepreneurs and transportation to independent carriers. In such cases, integrated models cannot be used to ensure the performance of the supply chain. Coordination mechanisms need to be defined and optimized in order to guarantee the best usage of the forests for the owner. The most traditional approach would be to set pricing strategies or to set open markets supported by auctioning mechanisms. The impact of such approaches needs to be addressed in regard to the planning of the forest supply chain.

Open Problem 10 *How can we develop methodology to coordinate and synchronize a set of stakeholders with individual agendas?*

Another important reason for tactical planning is tied to the seasonality of the supply chain, which increases the need for advance planning. Seasonality has a great influence on the procurement stage (i.e., the outbound flow of wood fibre from the forests). One reason for this seasonality is the shifting weather conditions throughout the year, which can make it impossible to transport logs/chips during certain periods due to a lack of carrying capacity on forest roads caused by the spring thaw, for example. In many areas of the world, seasonality also plays a role in harvesting operations. In the Nordic countries, for example, a relatively small proportion of the annual harvesting is done during the summer period (July–August). During this period, operations are focused on silvicultural management, including regeneration and cleaning activities. A large proportion of the wood is harvested during the winter when the ground is frozen, thus reducing the risk of damage while forwarding (or moving) the logs out of the forest.

Roads often need to be built to provide access for harvesting and transportation of timber to destinations such as ports, sawmills, pulp plants or stock yards. These roads can be made of different materials such as gravel, dirt or pavement, and upgrading of roads to allow use in poor weather, or allow for better transport is also an option. These models correspond to mixed integer LPs, where the road building decisions lead to 0–1 variables. These models have been in use for decades. A first implementation, in the 70s by the US Forest Service, solved in separate models the harvesting and road building decisions. Mixed integer formulations were developed by Weintraub and Navon (1976), Andalaft et al. (2003), and Kirby et al. (1986). Flisberg et al. (2014) has integrated road upgrading with the inclusion of harvesting and transportation.

Open Problem 11 *How can we model and solve integrated harvesting, transportation and road building for large-scale forests considering spatial and environmental constraints?*

5 Spatial and environmental concerns

Sustaining forest health and viability requires careful management of this renewable resource in a multi-use environment. Such management has come to include addressing explicit spatial and environmental concerns. This is important because harvest activity can lead to soil erosion, decreased stream and river water quality, disruption or loss of native species and degraded scenic beauty. However, harvesting can also be beneficial beyond economic and industrial objectives as it can create needed open space for certain flora and fauna, reduce forest fire risk, and inhibit disease and infestation spread. Therefore, one facet of forest management is deciding how to treat standing timber over a horizon of several years to decades. This requires decisions on the sequencing of stands or cutting blocks for harvesting in order to satisfy temporal timber demands in an economically competitive manner. In addition, road engineering is a necessary consideration as well because roads provide access to harvest areas. Thus, the costs for providing road access impact management plan viability.

The problem is to decide where and when to harvest, as well as which roads to build (or maintain) as discussed in the previous section, but doing so in a way that meets timber demands while also taking into account spatial and environmental concerns. To this end, many spatial and environmental concerns can be viewed as either necessitating or limiting local disturbance through harvesting.

One of the classic papers in this area is that of Thompson et al. (1973), addressing issues associated with environmental impacts through the use of adjacency type constraints along with temporal even-flow timber output requirements. Using this, green-up constraints are also possible. Combined with the work of Kirby et al. (1986) that detailed a harvesting optimization model used by the US Forest Service incorporating decisions associated with harvesting unit and road linkage decisions, most spatial and environmental concerns can be addressed in some way. This is because adjacency restrictions with green-up requirements limit impacts associated with timber extraction and forest disturbance. In particular, a maximum impact area limit is established to restrict local activity for a specified duration of time. For the case of clear cutting, this corresponds to a maximum open area that is imposed on any management plan. Thus, from a modeling standpoint, the challenge has been to effectively impose a spatial limitation where no more than X hectares of contiguous land are harvested at any time. The idea behind this limitation is that when X is sufficiently small, the impacts of harvesting activity are minimized. However, operational costs dictate that X cannot be too small as this decreases potential profits due to the need for more road building and increased equipment set-up overhead. In the US, it is not uncommon to find maximum area impact limits of 47 ha.

In order to model this type of spatial restriction it is assumed that cutting blocks cannot exceed the maximum allowed area X. When this is true, harvesting decisions can be modeled using binary variables, with 1 indicating harvest of a block in a given time period, and 0 indicating no harvest. This means that it is possible to restrict any neighbouring blocks from simultaneously being harvested as their combined harvest area would violate the established limit. Murray (1999) has characterized this as the Unit Restriction Model (URM) approach.

Of course, having blocks defined such that any two neighbours represent a violation of the X area limit is mathematically convenient. However, GIS and high-quality forest inventory data illustrate that greater spatial detail actually exists for many management regions. It is often the case that information exists on cells within blocks. For example, if X is 47 ha and our blocks are 40 ha on average, it would not be unusual to encounter cells within blocks of 1–10 ha. The complication with such a situation is that our limit, X, is substantially greater than cell sizes; so many cells can be simultaneously harvested before the X threshold is reached. This represents a combinatorial problem, where there are many ways to cluster or block cells. Murray (1999) refers to this as the Area Restriction Model (ARM).

The URM and ARM distinction highlighted in Murray (1999) is noteworthy for articulating the fundamental difference in approaching the basic harvest scheduling problem to address spatial and environmental concerns. This difference is predicated on the representation of space, data availability, and how maximum area impacts are modeled. A considerable amount of work has followed on harvesting problem formulation (reformulation) and solution.

Computational challenges have generated research in two directions for solving harvest scheduling problems accounting for spatial and environmental concerns. One research direction is heuristic solution development. For the URM, techniques like Monte-Carlo integer programming, simulated annealing, Tabu search and genetic algorithms were developed to heuristically solve harvesting models. For the ARM, artificial intelligence based heuristics for problem solutions were initially developed, later followed by simulated annealing and Tabu search heuristics. Another direction of research has focused on exact solutions approaches. For the URM, specialized methods have been successful, like column generation and dynamic programming. In addition, constraint structure has been enhanced through constraint aggregation and lifting. Higher ordered clique constraints in particular have been very successful in imposing adjacency restrictions in a manner that makes solution by exact methods computationally feasible. For the ARM, McDill et al. (2002) first posed an integer programming formulation amenable to exact solution based on enumerating block violations. Goycoolea et al. (2005) and others focused on enumerating feasible potential blocks using cells, but also incorporating facets and cliques. This substantially increased capabilities for solving relatively large planning problems with many time periods with modest computational requirements. A summary of algorithms developed for spatial problems is presented in Goycoolea et al. (2009).

With all the success and strides that have been made in structuring and solving URM and ARM approaches, there remain considerable challenges in modeling to support harvest scheduling addressing spatial and environmental concerns. We have only begun to explore capabilities for modeling cell based models imposing an X area limit. In particular, larger and more constrained problems will no doubt arise in the future as better spatial information becomes accessible. Beyond this, there has been little research to date exploring the potential for including roading decisions in cell based, X restricted tactical models. Alter-native approaches for addressing environmental conditions also represent an area for future research. In particular, there is a need for explicitly addressing issues like preserving certain habitat like old growth in the context of harvesting. On the one hand, this preservation issue resembles notions of reserve design and promoting biodiversity undertaken by conservation biologists. On the other hand, it does not make sense to believe that habitat can be completely shielded from multiple-use activities. Thus, greater integration of planning for a wide range of concerns (e.g., harvesting, preservation, recreational use, etc.) must be carried out if sustainability is to ever be achieved.

Open Problem 12 *How can we develop exact models and methods for the ARM for large-scale problems involving thousands of cells and many time periods, along with road building and maintenance decisions?*

It is well recognized now that adjacency constraints capture only a part of necessary environmental considerations. While maximum opening size limits are important, excessive fragmentation of forests is not particularly satisfactory. In order to allow wildlife to move between habitats, corridors of mature trees need to exist to join them. Similarly, issues of forest edge as well as a balance of mature forest are important for certain species. A few examples exist of attempting to address related issues using heuristic approaches. Thus, exact approaches are needed.

Open Problem 13 *How can we include complex environmental considerations like fragmentation, corridors, balancing mature patches, etc. into URM and ARM formulations in a computationally feasible way?*

6 Strategic forest management

Strategic forest management decisions create and define the resources available to the forest enterprise in terms of the land base, the industrial capacity and the rules that govern the use and allocation of the forest resource. Different strategic decision makers will legitimately make different strategic choices, Gunn (2009). There is a long history of LP models for evaluating forest strategy and it is these models that we are addressing. Strategic planning is considered both at governmental level as well as for forest industries. However, it is not only the linear programming technology that is at issue. Many jurisdictions use simulation models that address similar issues and produce similar results.

Today it is widely accepted that forest management means sustainable forest management (SFM) related to conservation of biodiversity, soil, water, ecosystems and productivity, as well as social issues. Most jurisdictions have developed formal SFM criteria and indicators, from international processes. Many countries have also developed their own criteria and indicators.

The second major driver on forest management strategy is the recognition of the complex and increasingly integrated supply chain of forest products. At the strategic level firms need to consider the whole supply chain, from forests to plants, to distribution to final clients, with decisions involving plants, markets, and distribution systems.

The economic performance of this supply chain depends on the amount, quality and cost of the raw materials. Economy of scale issues tend to lead to large processing plants with some of the outputs of these plants being inputs to others. Their location relative to the forest resource, and to each other, can have considerable impact on transport costs, which can be a substantial component of overall costs. When just considering forests, both private and public, strategic decisions involve long-range, aggregate harvesting and planting decisions.

The first implemented strategic LP model was carried out by the US Forest Service (Navon 1971), which was used to plan long-range harvesting. The extensive use of a strategic forest management model in the private sector dates back to Ware and Clutter (1971) although the ideas go back much further. Considerations of broader issues than timber harvest led to the development of MUSYC, FORPLAN (Kent et al. 1991), and SPECTRUM within the USDA Forest Service. Similar developments have taken place in Europe (see e.g., Heureka, Wikström et al. 2011).

Typically, strategic forest models will consider units or stands considered homogeneous in terms of including species, age, site quality, but not spatial connectedness. This aggregation allows for considering significantly smaller LP models, and at strategic level spatial definitions are not really needed. However, as will be discussed in the hierarchical planning section, the strategic level must be consistent with the tactical and operational ones, in terms of harvesting, and particularly in relation to environmental issues. The horizon of these models is usually two or more rotations, to include harvesting and planting in a long-range view.

There are several models to represent the strategic harvesting problem (Martell et al. 1998). Model I defines multiple prescriptions for each unit through the horizon, and the model must decide which prescriptions to use. Another approach, called Model II, groups units harvested in the same period. Growth and yield models have been developed which estimate well the volume of timber that can be harvested in future periods, under different management or silvicultural options.

These options can be viewed at two levels. At a higher level the overall strategy is considered: does the organization wish to produce high-quality logs which will require thinning, pruning and other measures which induce higher costs; how does timber production relate to the needs of the plants downstream; or for long-term production plans or contracts, how are environmental considerations considered? At a more detailed level, as discussed in Models I and II, specific harvesting and planting decisions are defined.

Decision making in any industry normally occurs in an environment of considerable uncertainty. In addition to the normal uncertainties of prices, markets and exchange rates faced by any business, forestry is subject to large-scale natural disturbance events, including fire, insect attacks and hurricanes, and other large-scale wind events in addition to uncertainties of growth and yield of the forest. These latter uncertainties in turn are affected by larger uncertainties of climate change.

Uncertainty in future events creates several challenges: how to define it quantitatively, how to model planning models that explicitly consider uncertainty, and how to solve these far more complex problems. In the 80s several proposals involving uncertainty in tree growth were proposed, mainly through chance constrained models (Martell et al. 1998). Some efforts to consider uncertainty in markets and tree growth defined through scenarios have been proposed, but at the tactical level (Badilla Veliz et al. 2014).

Open Problem 14 *How can we explicitly and rigorously evaluate and introduce different kinds of uncertainty into strategic models, and how can we solve these models?*

A vital issue in strategic planning is the environment and sustainability. Biodiversity, ecosystem conditions, watershed conditions, wildlife preservation are among the core environmental issues. Often, considering environmental protection implies spatial analysis, such as riparian zones that limit basal area removals, maximum opening size, and large areas with continuous old growth trees to protect wildlife. Finding compromises that satisfy needs of different species can be complex, and all these measures affect the productivity of the forest

Sustainability is a related issue. Environmental considerations require sustainability of the multiple values in the forest. These issues are fuzzy, difficult to rigorously measure and often conflicting. At the same time, timber production also should be sustainable for socio-economic reasons.

Open Problem 15 *How can we incorporate the different environmental and sustainability issues into models and solve the resulting models?*

Open Problem 16 *How can we visualize and model strategic forest planning within the whole supply chain, with multiple independent stakeholders along the chain? How can we evaluate any equilibrium that will emerge?*

7 Wildlife conservation

As human populations grow and convert wild land to urban, forestry, and agricultural uses, people become concerned about the loss of wildlife habitat, biodiversity, and ecosystem services. In response, governments regulate land use and raise billions of dollars to acquire and protect open space to meet a variety of needs, including wildlife conservation. Planners involved in wildlife conservation belong to government agencies, wildlife conservation organizations, and forest product industries, and they make difficult decisions about what lands to set aside for wildlife habitat and open space. Trade-offs and conflict are inherent in these decisions. In urban or urbanizing areas in particular, wildlife habitat and open space are often badly needed but available land may be very limited and very costly. Furthermore, species of interest often need different types and amounts of habitat.

Recognizing that resources are limited and land use pressures from population and economic expansion compete with habitat protection, biologists, operations researchers, and economists have explored models to help rationalize the choice and assembly of habitat reserves. An outcome was the development of models that maximize the diversity or viability of species subject to budget or resource constraints. In forest management, LP models were developed to allocate lands to mutually exclusive (and sometimes complementary) uses of timber production and wildlife habitat (Hof and Bevers 1998). Researchers later formulated 0–1 linear IP models for habitat protection where the choice variables represent whether or not to protect specific sites. The main advantage of formulating habitat protection problems as IP models is site specific policy guidance, including habitat protection activities that efficiently achieve wildlife conservation goals and efficient tradeoffs between conservation goals and protection costs. Researchers quickly recognized this advantage and formulated habitat protection problems with a remarkable array of objectives and constraints.

We review the current status of three types of models that inform planners involved in wildlife conservation: reserve selection and design models, stochastic demographic models, and urban economic models. We attach specific meaning to the terms *site*, *reserve* and *reserve system*. A site is a selection unit—a piece of land that may be selected for protection. A site is usually undeveloped open space belonging to one or more cover types, including forest, grassland, pasture, or cropland. A reserve is a single site or a contiguous cluster of sites that has been selected for protection. A reserve system is a set of multiple, spatially separated reserves. We also distinguish reserve selection from reserve design models. Reserve selection models identify sites to protect to maximize some measure of biological diversity (e.g., species richness) subject to a budget constraint with no consideration given to the spatial attributes of the reserve system. Reserve design problems, on the other hand, use spatial attributes of the reserve system as objectives. Excellent reviews of reserve selection and design principles and models are available (Moilanen et al. 2009).

Reserve selection models are typically IP formulations with many counterparts in the location science literature (see ReVelle et al. 2002 for review). The pioneering reserve selection models addressed a species set covering problem. Given the distribution of species among sites and the cost of reserving each site, the model selected the minimum cost set of sites that covered all of the species. The species set covering problem was the springboard for extensions. The maximal species covering problem (MSCP) was formulated to select sites for protection to maximize the number of species covered subject to an upper bound on the number or cost of the protected sites. The MSCP has been modified to include backup and redundant covering requirements. While the MSCP focuses on the single objective of maximizing species representation in protected reserves, additional conservation objectives can be considered in bi-criteria formulations, including spatial attributes of the reserve systems, total habitat area, habitat quality, and public access or proximity. The MSCP and extensions have been used worldwide, and LP plus branch and bound has been successful in finding optimal solutions to many of the largest applications with thousands of decision variables.

An important extension of the MSCP involves the recognition that species presence is not known with certainty but with some probability. Using a matrix of probabilities of species presence in sites, researchers developed the maximal expected species covering problem (Camm et al. 2002). Because expected species coverage is the sum of terms involving the products of the site selection variables, the problem cannot be converted to an equivalent linear integer programming problem; however, solving a linear approximation of the nonlinear program using LP and branch and bound can yield good solutions to very large problems. The maximal expected species covering problem can be further enhanced using chance constraints that require selected species, for instance those that are particularly endangered, to be covered with a minimum level of reliability (Arthur et al. 2004). The chance constraints can be converted into linear equations, and LP and branch and bound can be used to solve for tradeoffs between conservation objectives of maximizing the protection of endangered species versus maximizing species richness.

One shortcoming of maximal species covering problems is that they do not consider the spatial distribution of selected sites. Consequently, solutions may consist of scattered reserves that may not support the long-term persistence of species and may increase the difficulty and expense of reserve management. Accounting for the spatial location of protected sites may be necessary to enhance habitat quality and ensure dispersal of wildlife populations. The MSCP problem has been extended as an IP formulation to include spatial criteria such as reserve proximity, connectivity, and shape (see Williams et al. 2005 for review). A typical reserve design problem is to select sites that optimize a spatial criterion while meeting species coverage and budget constraints. For example, many authors advocate creating compact reserves of minimum size. Compact reserves are better for edge-intolerant species that prefer large areas of interior habitat. One approach to forming reserves that meet size and shape requirements is to predefine desirable clusters of sites and include the clusters as decision variables in a site selection model that maximizes the area of reserves that meet a contiguous size requirement. Another approach involves maximizing the number of inner protected reserve areas each surrounded by a ring of land managed to buffer the core area from negative impacts of the surrounding landscape. A third approach involves selecting sites to minimize the measure of compactness of the resulting reserves, where compactness is the total length of the reserve boundaries. These and other reserve design models have been successfully formulated as IP problems and solved for real-world applications.

The problems described above assume that decisions are made all at once and ignore potential effects of site selection decisions on land markets, development patterns, and qualities of unprotected sites. In practice, site selection decisions are sequential as budgets and political support allow, and planners want to account for uncertainties in land development, availability, and price. Stochastic dynamic programming has been used to develop selection strategies for problems with an objective of maximizing the expected number of species protected and accounting for uncertainty in site availability; however, computational limits prevent solution to problems with more than about ten sites. Researchers are beginning to develop IP models that can address larger problems.

Snyder et al. (2004) developed a two-period IP model for sequential site selection in which uncertainty about future site availability is represented with a set of probabilistic scenarios. The two-period problem maximizes the expected number of species covered at the end of the second period subject to an upper bound on the total cost of site protection. Toth et al. (2011) develop a multi-period reserve selection model that accounts for the effects of site selection decisions on land markets. Their IP formulation accounts for changes in the regional price of land associated with changes in supply and demand. It accounts for land price increases in the neighbourhood of existing or newly created reserves due to increased amenity benefits.

There is still a great deal of work to be done on formulating and solving dynamic reserve selection and design problems to better account for changes in land prices, land development, conservation budgets, and habitat quality. Since many of these processes are stochastic, there are significant computational challenges.

Open Problem 17 *How can we develop effective formulations and solution methods for dynamic reserve selection and design problems with land price feedbacks and uncertainty about site availability, quality and budget?*

Ensuring species survival has long been an objective of wildlife conservation, and reserve selection and design models that account for species survival probabilities have been built with increasing levels of biological detail. Species survival can be indirectly related to design features such as number, size, habitat quality, and spatial arrangement of reserves. Therefore, the problem is to maximize the number of species covered where a species is covered only if a minimum area or arrangement of sites is achieved. Otherwise, species survival probabilities can be directly related to reserve design features and the problem would be to maximize the expected number of surviving populations subject to cost constraints. Reserve selection models with even more biological detail include deterministic equations for population dynamics. Models seek to maximize population size where population growth and dispersal are related to reserve design (Bevers et al. 1997).

The field of conservation biology contains a long line of research in the development of stochastic demographic models of population viability, which are commonly used to inform wildlife management decisions (Akcakaya et al. 2004). Researchers are just beginning to incorporate them into reserve selection models with the objective of maximizing species survival probabilities. One approach is to use response surface analysis and create relatively simple relationships between reserve design features and species survival probabilities based on Monte Carlo experiments with the stochastic demographic model. Those simple relationships are then included in an optimization model to determine the best design features. Another approach is to optimize the stochastic simulation model directly using search heuristics together with variance reduction techniques to limit the number of replications required at each search point.

Open Problem 18 *How can we incorporate stochastic demographic models of wildlife population viability into reserve selection problems?*

Almost all wildlife conservation planning tools ignore public welfare, and there is growing recognition that resulting information about priorities and tradeoffs for habitat protection may be unsatisfactory, especially in metropolitan areas with ongoing land development. A more sophisticated analysis needs to incorporate local spatial heterogeneity in both ecological and social variables and include household welfare in addition to biodiversity goals. The field of urban economics provides direction for this type of analysis. Urban economic models predict the spatial pattern of land use and housing development derived from structural economic models of residential location choice; (see Irwin (2010) for review). One approach is to build a discrete space model of an urban area and to determine the optimal provision of open space given a planner's objectives of maximizing household welfare and maximizing a measure of biodiversity conservation (Tajibaeva et al. 2008). More work is needed to incorporate social and economic models of residential location choice into optimization models for reserve selection to determine the feedbacks between the biological and social systems.

Open Problem 19 *How can we incorporate social and economic models of residential location choice into dynamic reserve selection models to maximize household welfare and biodiversity conservation?*

8 Fire management

Fire is common in many forest and wildland ecosystems, particularly in temperate forests that are dominated by flammable coniferous tree species such as the circumpolar boreal forest that stretches across northern Canada, Scandinavia, Russia and Alaska, and more southerly forests that experience Mediterranean climates like those in parts of southern Europe, southern California, and Australia in which flammable trees, brush and other vegetation endure intense, fast spreading fires.

Forest or wildland fire is a destructive force that can and sometimes does harm fire fighters engaged in suppression operations and residents who become trapped by fast moving wind-driven fires that sweep across populated flammable landscapes. Fire burns homes and forest resources and often disrupts transportation systems and other infrastructure. The risk of fire and the smoke that it emits is a public health threat that sometimes forces the evacuation of communities. It can also disrupt recreation activities and destroy wildlife reserves that have been set aside to protect endangered species. It is therefore not surprising that fire has traditionally been viewed largely as a destructive force that was to be eliminated from forest and wildland landscapes at almost any cost.

Although fire is often destructive, it is also a natural process that is essential for the maintenance of many forest ecosystems. Consider, for example, Jack Pine (*Pinus banksiana*) trees which are common throughout the boreal forest region of Canada. Jack Pine has serotinous cones, most of which remain sealed by a waxy resin until the heat from a fire melts the resin. The cone can then release its seeds onto the mineral soil seed bed that is exposed after the moss and litter on the forest floor have been burned. A fire that destroys a Jack Pine stand therefore initiates the birth of a new Jack Pine stand on the burned site and plays an essential role in the maintenance of Jack Pine ecosystems.

Fire also plays an important role in reducing hazardous fuel build-ups in many forest ecosystems. In the intermountain west of Canada and the United States for example, Ponderosa Pine (*Pinus ponderosa*) has a thick, fire-resistant bark and is able to survive frequent, low intensity fires. On these sites, surface fires consume dead cured grass and make it difficult for other species such as Douglas-fir (*Pseudotsuga menziesii* subsp. *Glauca*), to survive. Fire suppression makes it possible for such species to become established in the understory where then serve as ladder fuels that support the initiation and spread of intense, destructive crown fires that kill mature Ponderosa Pines, many of which would survive lower intensity fires.

Fire managers must decide when and where to suppress wildfires and when and where to light prescribed fires or allow wildfires to burn. Given the very diverse range of social, economic and ecological impacts of fire on people, property and forests, it's very difficult for fire managers to identify and achieve an appropriate balance of the beneficial and detrimental effects of fire at a reasonable cost.

Operational researchers have worked with forest fire managers since the 1960s when Shephard and Jewell (1961) initiated research on OR applications in forest fire management at the Operations Research Center at the University of California, Berkeley. Much of the research that took place during the 1960's and 70's is described in Martell's (1982) literature review. Most of the operational researchers that have studied fire problems have focused on fire suppression operations in support of traditional fire exclusion policies but some have explored fire and forest management planning under uncertainty due to fire (e.g., Reed and Errico 1986). However, few have tackled the complex social, economic and ecological issues that complicate modern forest fire management.

One of the greatest challenges to forest fire managers is to determine how best to achieve an appropriate balance between the many costs and benefits of forest and wildland fire on flammable landscapes that are used for residential, industrial and recreation purposes, and also provide valuable habitat for many species of plants and animals, some of which are threatened or endangered. Expanding upon Martell's (2007) supply chain logistics analogy, fire managers have to determine how to deliver the *right amount of the right fire to the right place at the right time at the right cost.* The fact that fire costs and benefits have many important social, economic and ecological dimensions that span very broad spatial and temporal scales under considerable uncertainty complicate already significant challenges for both fire managers and operational researchers who choose to help resolve many complex decision-making problems posed by fire management.

Fire managers have long known that vegetation, or what they commonly refer to as fuel, has a very significant influence on fire ignition, spread and intensity and the ability of fire fighters to contain fires. Fuel breaks are areas, typically long corridors, where flammable fuels have been removed and/or replaced by less flammable fuel complexes. They can be used to fragment otherwise continuous fuel complexes to mitigate fire spread and also as anchor points for suppression action; for example, the ignition of "backfires" in advance of intense, fast moving, wind driven fires. One of the earliest fire management applications of OR was Davis (1964) who used gaming simulation techniques to elicit subjective assessments of fuel break effectiveness from fire managers. He then used those effectiveness assessments to evaluate fuel break strategies by assessing how well specified strategies would have performed on historical fires in California.

Fire suppression has, as we noted above, contributed to fuel build-ups in parts of the United States, Australia and other countries, which in turn, have contributed to more intense fire behaviour, escalating suppression costs and fire losses. The Joint Fire Sciences (JFS) research program in the United States has supported many fuel-management-related research initiatives and, not surprisingly, the JFS program and other organizations have funded many attempts to bring OR expertise to take on fuel management problems. Many authors have coupled Geographic Information Systems (GIS) technology which is used to map fuel and topography, with fire spread models to predict how specific fuel treatments or classes of fuel treatment will impact fire spread. The majority of these models are simulation models that have been applied to large landscapes, but there have also been a small number of attempts to develop mathematical programming fuel management models that have been applied to small representative, hypothetical planning problems (e.g., Wei et al. 2008; Minas et al. 2014).

Fire spread is a complex process that is driven by fuel, weather, topography and suppression action, and it's also influenced by spotting, which occurs when firebrands emitted from the main fire are blown ahead of the main fire front where they ignite new fires. Even if these spot fires are ignored, the fuel management problem can be viewed as a very computationally challenging dynamic stochastic integer programming problem with complex fire ignition and spread scenarios. The fact that some effects of fuel management decisions implemented during any period may persist for several periods simply complicates an already difficult problem. Fuel build-ups, climate change and the need to manage fire on increasingly complex built landscapes on which people are establishing more and more homes and recreational properties and other infrastructure will exacerbate a class of problems to which operational researchers can contribute.

Open Problem 20 *How can we develop tractable models that can be used to help determine when and where to implement fuel treatments on large flammable forest and wildland landscapes?*

Many forest fire management agencies use amphibious or land-based airtankers for initial attack on small fires and occasionally, to cool selected portions of large escaped fires. Some fire management agencies own airtankers while others lease them from private air carriers for all or part of the fire season. Airtankers are home-based at airports close to areas where they are expected to be most needed, but fire activity and the need for airtankers vary significantly over both time and space so fire management agencies often supplement their airtanker fleets with airtankers temporarily borrowed from other agencies or leased from private operators on short-term contracts. Each day managers predict where fires are most likely to occur and then deploy their airtankers and those they acquire on short term leases at bases where they expect they will be most needed that day. Daily deployment decisions are sometimes revised as the day progresses if and when the dispatchers realize the day is unfolding differently than was originally anticipated.

Although many forest fire management agencies use airtankers, some use other types of equipment instead of or together with airtankers, for initial attack purposes. Recent years have witnessed growing interest in the use of stochastic integer programming (SIP) methods to help determine how best to deploy and re-deploy fire engines (e.g., Haight and Fried 2007) and dozers (e.g., Ntaimo et al. 2013). Those that have applied SIP methods to the deployment and dispatch of engines and dozers assumed such equipment is dispatched to at most one fire per day which is a reasonable assumption given the way most agencies use such equipment. However, it is not clear how well SIP methods will perform if they are applied to the management of airtankers which can be and often are dispatched to several fires on a busy day.

Airtanker systems can be modelled as spatial queueing systems with airtankers as servers and fires as customers that arrive at different rates throughout each day where the time required to "serve" a fire depends, in part, on its size at initial attack (see, for example, Islam et al. 2009). Time-dependant spatial queueing system models that predict airtanker system performance in terms of initial attack response time as a function of where the airtankers are deployed at the start of the day and dynamic policies that prescribed how they should be re-deployed as the day progresses could be used to inform daily airtanker deployment and re-deployment decision-making.

Open Problem 21 *How can we develop spatial time-dependant queueing models that can be coupled with tractable optimization models to be used to help determine how to best deploy airtankers at the start of each day and how to re-deploy them as the day progresses?*

Most forest and wildland fires are controlled by small initial attack forces but a small fraction of the fires that escape initial attack can grow to large sizes and it is that small number of large escaped fires that contribute most to the area burned. In the province of Ontario, for example, the initial attack force is typically four fire rangers that travel to the fire by truck or by helicopter. They may or may not be assisted by one or more airtankers that scoop water from lakes near the fire and drop that water on the fire under the control of an air attack officer until he or she passes the management of the fire over to the leader of the fire ranger crew on the ground who becomes the incident commander on the fire. Roughly 97 % of the fires in Ontario are contained at small sizes by the initial attack force. Escaped fires can grow to hundreds of thousands of hectares and pose significant challenges to fire managers who must develop control strategies that balance the risk for fire fighters and fire damage given considerable uncertainty concerning future weather and fire behaviour, the availability of fire suppression resources, and their productivity.

Large fires are managed by Incident Management Teams (IMTs), the size of which depends upon the size and complexity of the fire being managed. A full IMT in Ontario is typically made up of about eighteen individuals who are led by an Incident Commander (IC). Large fires pose many interesting challenges to IMTs. The IMT has to gather information concerning the fuel and topography in the fire area as well as current, short-term and long-term forecast weather. That information is coupled with their knowledge of the values at risk as well as the potential ecological benefits of the fire to develop both a short-term daily Incident Action Plan (IAP) and a longer term strategic plan. Those plans and strategies might call for aggressive suppression of some portions of the fire perimeter, allowing some parts of the fire to burn into defensible boundaries such as lakes and rivers and ground, or aerial ignition of fire might be done to burn out fuels in advance of the fire. They can also include allowing some portions of the fire to burn freely, and the deployment of structural protection units (e.g., sprinklers) to protect structures that might be threatened by the fire.

Mees et al. (1994) developed one of the first single large fire suppression optimization models and more recently, Wei et al. (2011) developed a mixed integer programming approach to the problem. More recently, the USDA Forest Service (2014) developed and now uses the comprehensive Wildland Fire Decision Support Systems (WFDSS) which is designed to be used to support the management of large fires.

Deciding how and the extent to which a large fire should be contained are, in many respects, similar to the strategic fuel management problem of deciding when and where to implement fuel treatment activities. The differences are in scale (much shorter temporal and spatial planning horizons) and the fact that suppression action interacts with and thereby shapes the spread of the fire. As is the case with landscape level fuel management, the problem of determining how best to manage a large fire (e.g., what suppression resources to allocate to each segment of the fire perimeter over time, when and where to use fire to burn out fuel in advance of the fire, and when and where the fire should be allowed to burn out to defensible boundaries such as lakes and rivers) can be modelled as a very challenging stochastic integer programming problem.

Open Problem 22 *How can we develop large fire management decision support systems that can be used to help determine how to best manage a large fire that has escaped initial attack and may pose significant threats to people, property and forest resources while it enhances natural ecosystem processes under uncertainty?*

9 Value chain management

Value chain management (VCM) addresses coordination of a set of organizational units involved in bringing to market wood fibre-based products through management, engineering and planning decisions. The objective is to enhance the performance of the units as well as the whole chain. These units are responsible for many different activities which are conducted within diverse environments. These cover forest management, silviculture, harvesting, transportation, production, distribution, sales, return, and recycling.

As opposed to function-based planning such as transportation or production planning, VCM aims to integrate and synchronize a number of activities and business units within the planning process in order to reach more efficient solutions. It is challenged with balancing supply with capacity and demand in a distributed environment where units are independent and making their own decisions but all interconnected to deliver maximum values to the stakeholders. These values may vary according to the decision makers' perspectives. They can be grouped under economic, social or environment values, the three pillars of sustainable development. In the forestry literature they are often referred as either timber value or non-timber value. In forestry VCM proposes a new holistic approach to the management of the forest value chain, recognizing the multiple contributions and the tight links between community development and long-term sustainable resource planning with economical considerations of balancing demand, capacity and supply.

Therefore, D'Amours et al. (2008) describes forest value chains as complex adaptive systems driven by socio-economical, technological and environmental forces that extend in "time" and "space". For example, the growth of the forest may extend over a hundred years in some parts of the world and the value chain may be global, connecting units all over the world. They can be understood through three tightly connected sub-networks: the resource network, the production and distribution network, and the recovery network. The resource network manages the forest as well as the delivery of the forest products to the mills, and the eco-services to wildlife and communities. The production and distribution network transforms the wood into products or services, sells and delivers the goods to the markets. The recovery network manages the residues and end-of-life products to generate new values when possible. Value chain's units can be owned by public, para-public or private organizations (firms). The links between the units vary depending on country legislations and enterprise business models. The main business streams are pulp and paper (e.g. newsprint, fine paper, tissue and packaging), wood products (e.g. lumber, panels, and engineered wood products for structural or appearance application), and energy (e.g. green biomass, pellets, biogas). A number of emerging business streams are being developed at this time through the application of biorefineries and usage of the biomass (Stuart and El-Halwagi 2012; Machani et al. 2014).

In the value chains, one of the main challenges resides in the integration of the very long-term strategic planning of the resources network with the shorter time planning of its production, distribution and recovery networks, acknowledging the tight links between multi-objectives agents (e.g. collectivities, governments and industries) which either collaborate or, in some cases, compete for resources (e.g. logs, equipment, capital). Traditionally, the forest industry has been defined as a commodity industry where products are sold when available. However, as more demand-driven and contract-based relations between customers and producers are being observed, synchronization of the different activities (e.g. flows and resources allocation) of the value networks in order to meet market demands is needed. This raises methodological challenges as the forest and its industry are characterized by divergent flows. Many processes, for example bucking, sawing, cutting and converting, are producing mix of co-products and by-products. Co-products are defined by products for which a demand exists while by-products are obtained through the process and normally have very little value for the producer. The aim is to manage all the activity of the chain to maximize the value obtained from the fibre, understanding its characteristics and its impact on meeting demand and logistics costs.

In value chain planning, planning processes are hierarchically structured. Strategic decisions are setting critical capacities and business strategies. These constrain the tactical planning process that defines policies and rules for allocating resources. Tactical planning transfers constraints to the operational planning process that defines how to use the resources to meet the demand. In fact, all of this planning effort is asynchronous and requires feedback from execution to strategic planning. The planning horizon stretches from hundred years (forest management) to half a century (e.g. new capacity investment in pulp and paper mills), down to hours and minutes (e.g. operative truck routing), and even seconds (e.g. bucking optimization).

The planning of the value chain often implies a framework which builds on collaborative planning concepts. Notably, often the value chain's units are autonomous and driven by different owners' objectives. In some countries where forests grow on crown lands, the forest activities are more or less decoupled from the industrial activities the need for community-based forestry and industry development challenges the decision makers. Moreover, in environments where many forest users have to share access to the resource, cross-chains coordination (e.g., in logistics) shows an opportunity to improve value chain performances (Frisk et al. 2010).

Several surveys exploring the different perspectives on the forest value chain can be found in the literature today. Some reviewed the contribution of OR to the forestry industry, focusing on issues related to forest management, harvesting and transportation to wood-consuming industries (Rönnqvist 2003; Martell et al. 1998; Epstein et al. 1999). More recently, these surveys were completed by including OR contributions in the planning and distribution of forest products such as paper, lumber, engineered wood products, forest fuel and biofuel (Gunnarsson et al. 2004; Carlsson et al. 2009; D'Amours et al. 2008). In general, the quality of forest management and forest operations has an important and direct impact on the performance of the different wood fibre value chains. The *Handbook on Operations Research in Natural Resources* (Weintraub et al. 2007) and the *Management of Industrial Forest Plantations* (Borges et al. 2014) present articles showing multiple topics related to forest modeling, considering different hierarchical levels, spatial and environmental issues, and stochastic and multi-attribute approaches.

The value chain concept raises a number of issues. First, it requires that demand information for end products and services be considered within the planning processes. This chain of demand information is fairly new in forestry, and therefore, challenges managers in how they can share it and can make good use of it, especially, when this information is proprietary to different business units of the chain. Moreover, from a process perspective, the forest value chain is defined by a sequence of divergent processes which render the traditional use of dependent demand-based approaches inefficient (e.g., Manufacturing Resource Planning Systems). To our knowledge, demand-based planning approaches for divergent process environments are in their infancy phases and are still viewed as an open problem, particularly when safety stock issues are considered.

Open Problem 23 *How can we develop an integrated planning framework for demand-driven VC characterized by a sequence of divergent processes?*

Even though we can set plans for the different components of a value chain, the next step remains in coordinating these plans across units. The forest sector is particularly challenged by this need as the different units of the VC may express divergent objectives and strategies that do not permit centralized or integrated planning. In such a case, coordination mechanisms are required to efficiently help the units maximize their benefits while integrating a VC. These mechanisms are of different forms (e.g., shared information, auction, contracts, collaboration, transfer prices, legislation, etc.). Although they are key to the alignment, we know very little of how the mechanisms perform, how they should be combined and used, how they can alter forest and industry over time, etc.

Open Problem 24 *How can we design the coordination mechanisms needed to integrate and synchronize the units within the forest value chain?*

In the VC, the planning problems can be very large, as they typically deal with many units, many products, many processes and many planning periods, with multiple objectives, large sets of constraints and different levels of uncertainty and risk. They are often dealt with large scale network based models which requires advanced solving approaches. At this time, large scale multi-objectives and stochastic, multi-stages planning problems are not solved.

Open Problem 25 *How can we solve large scale multi-objectives and stochastic, multi-stages planning problems?*

10 Methodological challenges

10.1 Uncertainty planning

Most models that deal with timber and its products at different decision levels consider the future as deterministic and take as parameters expected values. There are important elements of uncertainty that should be considered in more detail. These include future markets where there is uncertainty in both prices and demand levels. As historical data shows, there is important variability in market prices, and there is often a significant independence for prices in pulp, saw-timber and in particular use of wood for energy. The latter is typically driven by the energy markets including petroleum and gas.

There may also be uncertainty in terms of volumes to be delivered or produced. There are many sources of uncertainty including timber growth, estimate on number and average size of trees per hectare, estimate on species proportions, partial harvesting, pruning and inaccurate production, harvesting and transportation plans. There are also uncertainties or risks associated with catastrophic events, such as climate uncertainty, fires, storms and pests.

When uncertainty is dealt with, deterministic methods are often combined with some hedging against shortage strategies. A typical example is to use safety stock to protect against demand uncertainty. Others are to include a certain percentage below the expected value, or to consider extra travel time for trucks (above expected set time). Deterministic methods are, however, fundamentally not developed for uncertainty. The literature shows several rigorous ways of handling uncertainty. One option is to use scenario planning where many scenarios are generated or analyzed independently. It is also possible to use more advanced methods like stochastic programming (SP) where many scenarios are analyzed together and robust optimization (RO).

10.1.1 Stochastic programming

Stochastic programming optimizes the expected or risk objective function value given a set of scenarios or with the continuous distribution of the random variables in a dynamic framework, usually finite horizon. Different solution techniques for stochastic optimization are used depending on the probability functions used to describe the randomness. When the uncertainty set is discrete and small, the deterministic equivalent model can be formulated (Birge and Louveaux 2011)

In SP there is an assumption that the uncertainty or randomness can be described by probability distribution functions; and therefore, scenarios used in the modeling can be described by a given probability. Depending on the complexity of the uncertainty and the number of stages, in practice these problems are sometimes very large and their solution remains challenging and difficult to solve within available decision time. However, there is an important and wide number of interesting solvable applications (Birge and Louveaux 2011; Gassmann and Ziemba 2012; Shapiro et al. 2014; Wets 1990).

Open Problem 26 *How can we represent uncertainty through scenarios for strategic, tactical or operational problems in forestry so that the underlying uncertainty is well represented in a solvable model?*

A scenario would be a defined price for timber for each period through the horizon. The future is then represented through a set of scenarios, with probabilities associated to each one. For these models a solution must be feasible under all scenarios, and the expected value over the scenarios is optimized. The advantage of this approach is that the solution protects against extreme scenarios, like a large drop in prices. Generating the scenarios is, however, a challenge in itself. On the one hand, there cannot be too many scenarios as the problem might not be solvable, but must cover all or most of the possible future events. These models need to include the non-anticipativity constraints, which state that if two scenarios have the same realization up to a certain period, then the solutions under these two scenarios must be identical up to the same period, as they share the same information. Adding these constraints leads to a much harder to solve problem if the number of constraints is large. Tactical planning models have been solved where decisions involve units to be harvested and road construction, needed for access.

In some cases the number of scenarios is large, and the problem cannot be solved directly. Several decomposition techniques have been implemented to allow solving the problem. Progressive Hedging decomposes the problem by scenarios by relaxing, in a penalized way, the non-anticipativity constraints. A forest planning problem involving harvesting and road building decisions, with uncertainty in market conditions and tree growth is presented in Badilla Veliz et al. (2014). Another approach is Coordinated Branching, where the non-anticipativity constraints are satisfied implicitly in the branching. A similar forest planning problem with market uncertainty is presented in Alonso-Ayuso et al. (2011). In both cases, introducing explicitly the uncertainty led to more robust solutions than the conventional deterministic modeling using expected values. Other approaches include Lagrangian relaxation, stochastic dynamic programming, chance constrained programming and simple average approximation.

Open Problem 27 *How can we express uncertainty for large, mixed integer, multistage problems where uncertainty is present in multiple sources, like fires, prices, and environment, so that uncertainty is well represented, in a solvable way?*

10.1.2 Robust optimization

Robust optimization deals with situations where the decision maker wants to be protected against parameter uncertainty and in particular against the worst-case scenario. A robust solution is a solution that is feasible for any realization of the uncertain parameters (Bertsimas et al. 2011). Much work has been done on static robust optimization where no recourse action can be done. However, when planning is dynamic on a rolling horizon, the solution can dynamically be adjusted as more information is known. In the dynamic planning situation there are two sets of variables. One set must be determined before all the parameters are determined (business decisions), and the other set of variables model future decisions that need not be determined until a later stage (anticipation decisions).

In RO there is no need to describe the uncertainty with any probability functions. Instead the uncertainty is described by lower and maximum intervals for unknown parameters together with some description of *budget of uncertainty* which limits the overall uncertain deviation of the parameters. This set is called the *uncertainty set*. RO searches for a solution that optimizes the worst case; and the main problem with RO is that a robust solution may be very conservative and costly as it imposes a large reduction in the objective function value.

Open Problem 28 *How can we correctly model the uncertainty in robust optimization?*

Recently there has been a large interest for robust optimization (See and Sim 2010) where the uncertainty set is kept small. The main problem with robust optimization is that solutions are over-conservative and often very costly. However, by introducing an uncertainty description where practical considerations are included, the solution can be much improved. This essentially means that additional information on the uncertainty can be included to considerably reduce the worst case scenarios. These ideas are used in Bredström et al. (2013) and Carlsson et al. (2014). These articles have dealt with the modeling of uncertain demand at heating plants and including large demand fluctuations of customers for pulp in a distribution problem for a large pulp producer. Although there are several case studies ongoing for various forest applications, it is not clear how these models can be used for daily practical planning and solved for large instances.

Open Problem 29 *How can we use robust optimization in practice for large mixed integer forestry planning problems?*

10.2 Hierarchical planning

The aim of hierarchical planning is to propose a decision making framework which integrates in space and time, the strategic, tactical and operational planning decisions. The hierarchical planning model also aims to be comprehensive and useful to policy makers, forest and business managers. Hierarchical planning is used to deal with the complexity of the planning problems which cover different objectives and time horizons. The consistency involves making sure those decisions taken at higher levels or for longer terms can be implemented at lower levels or for shorter terms in a feasible way, and involves preserving the costs and benefit values that were considered at the higher level.

There are several coordination mechanisms available to support hierarchical planning. One is to use anticipation modeling. In this approach, the model includes variables and constraints describing the behaviour of the lower level planning problem. Even if the solution of the anticipation variables are actually not used in the planning, they are very useful as they indirectly provide information to the implemented upper level variables. Another approach is to use bilevel models where the upper level provides policy decisions and the lower level models provide the feedback from potential several independent models.

Usually ad hoc procedures have been proposed to obtain these consistencies. Martell et al. (1992) report on proceedings of a workshop dedicated to this problem. Some specific proposals for hierarchical approaches have been developed. One proposal was to solve a forest LP model for the aggregate strategic level and then apply integer heuristics to obtain consistent spatial locations at the tactical level (Church et al. 1994). Another is to solve an aggregate forest LP model at the strategic level and then use the aggregate solution as input for the tactical level, which incorporates road building and spatially defined harvest stands (Weintraub and Cholaky 1991). In Cea and Jofre (2000) a two-level model is introduced linking strategic and tactical levels including mixed integer variables and disaggregation-aggregation procedures. Church (2007) discusses how tactical planning links strategic planning with operational decisions. In this regard, an important issue not quite settled is how to link decisions at different levels, so as to assure consistency between the decisions (Weintraub et al. 1997). In forest management, models rarely cover all of the supply chain. It is only recently that a holistic hierarchical planning model was proposed for the pulp and paper industry by Carlsson et al. (2009). The description defines the decisions to be taken at the level of the forest and their different links, as well as their impact on all the supply chain of a company.

As discussed, there are several approaches for specific cases that have been tested. However, there is a lack of systematic approaches to deal with consistency in a hierarchical approach.

Open Problem 30 *How can we implement consistent model decisions in a hierarchical framework?*

Usually in moving from one level to another, aggregation and disaggregation processes are carried out. For example, typically timber products are aggregated from specific products to global production as we move to more strategic levels. Also, as we move down from strategic level spatial definitions are incorporated. For LP models, there are well tested aggregation–disaggregation procedures, with defined technique to aggregate and disaggregate and with the possibility of having a bound on the error induced by the aggregation process. However, when integer variables appear, the aggregation-disaggregation problem becomes very difficult, as the results for LP models no longer apply. Integer variables appear in the case of road building or space specific activities.

Open Problem 31 *How can we develop aggregation and disaggregation processes when MIP models are used in hierarchical planning?*

10.3 Multiple criteria in forest resource planning

Multiple criteria are the rule rather than the exception in forest resource planning. Thus, every decision taken in this field affects several criteria of a different nature such as economic, environmental and social. In order to appreciate the role of the different multi- criteria decision methods in forestry, Diaz-Balteiro and Romero (2008) suggest dividing this type of problem into two groups: continuous and discrete problems. The former refers to problems for which the feasible set is characterized by the intersection of a set of constraints defined by inequalities and equalities, and, consequently, the number of feasible points is infinite. On the other hand, the feasible set of a discrete problem is formed by a finite number, usually not too large, of alternatives. A harvest scheduling problem is a typical example of a continuous problem, while the assessment of a finite number of feasible forest plans from the point of view of sustainability is an example of a discrete problem.

The approach most used in forestry, especially for continuous problems, is Goal Programming (GP). In this approach, decision makers define a target for each criterion. The model then minimizes unwanted deviations from the defined targets. A frequent variant used in forestry is weighted GP, though there is no rigorous way to define either the weights or how to aggregate them. The US Forest Service has incorporated multiple criteria into its planning tool SPECTRUM (1997), mainly in GP format. Another approach used in forest planning is multi-objective programming (MOP), where given conflicting objectives, MOP searches for the determination of a set of efficient solutions or a Pareto optimal set. These solutions are the feasible ones defined such that no other feasible solution can improve in one objective without deteriorating some other objective. The decision maker then has to choose one or several solutions from the efficient frontier. One application of this approach is in problems which have economic and environmental issues as conflicting objectives (e.g., Silva et al. 2010).

Other methods appearing in the forestry literature include MAUT, the Multi-Attribute Utility Theory, which aims at defining a cardinal utility function comprising all the relevant criteria, which is difficult to implement as it requires intensive interaction with the user, and AHP, the Analytical Hierarchical Process (Saaty 1977), where the decision maker's preferences are extracted via pairwise comparisons between criteria and alternatives.

Open Problem 32 *How can we incorporate the preferences of the decision maker for the different criteria into the multi-criteria model?*

Addressing this task will require some type of structured interaction with the decision maker. The complexity of this type of problem increases when, instead of a single decision maker, there are several stakeholders with different preferences with respect to the criteria considered. This type of realistic situation requires a certain merging of multi-criteria methods with group decision making techniques.

Most of the forest resource planning problems addressed from a multi-criteria perspective uses a single optimization method. However, the reliance on a single multi-criteria method is not justified in most of the applications. It would seem necessary to broaden the knowledge of the analyst in multi-criteria theory in order to facilitate the right combination of methods according to the characteristics of the problem analyzed.

Open Problem 33 *How can we develop multi-criteria approaches that are rigorous in thoroughly incorporating the decision maker's preferences, yet user friendly?*

11 Concluding remarks

We have described 33 open problems that are interesting for the field of OR in forestry. These can be used both to motivate research projects and as success stories once they are resolved. We wish all researchers the best in addressing the problems, and once these are solved we look forward to exploring new open problems.

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