Use of OR Systems in the Chilean Forest Industries

Rafael Epstein — Department of Industrial Engineering, University of Chile, República 701—Santiago, Chile

Ramiro Morales — Department of Industrial Engineering, University of Chile

Jorge Serón — Bosques Arauco Los Horcones s/n, Concepción, Chile

Andres Weintraub — Department of Industrial Engineering, University of Chile

The Chilean forestry sector is composed of private firms that combine large timber-land holdings of mostly pine plantations and some eucalyptus with sawmills and pulp plants. Since 1988, to compete in the world market, the main Chilean forest firms, which have sales of about $1 billion, have started implementing OR models developed jointly with academics from the University of Chile. These systems support decisions on daily truck scheduling, short-term harvesting, location of harvesting machinery and access roads, and medium- and long-term forest planning. Approaches used in solving these complex problems include simulation, linear programming with column generation, mixed-integer LP formulations, and heuristic methods. The systems have led to a change in organizational decision making and to estimated gains of at least US $20 million per year.

The Chilean forestry sector generates about 13 percent of all exports. Forestry exports include timber logs, pulp, and sawtimber. It is the second largest sector in the country after mining. The sector has grown at a rate of 12 percent a year during the last seven years and has good potential for further expansion during the next 20 years. The forest sector has been one of the drivers of Chile's amazing economic development during the last 15 years.

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The Chilean forestry sector is completely private, based mainly on large firms that own pine plantations (some eucalyptus too) and are vertically integrated with pulp plants, sawmills, and paper markets. Holding Arauco and Forestal Mininco (CMPC), the two largest companies, are among the 50 largest forestry firms in the world. Holding Arauco, which consists of Bosques Arauco and Forestal Celco, has 740,000 hectares of plantations and annual timber sales of about $300 million. In addition, it purchases timber valued at about $100 million. With its industrial products (pulp and sawtimber) its total sales are about $1 billion a year. CMPC, the other large firm, owns 490,000 hectares and has annual timber sales of $180 million. Timber purchases add another $120 million, and total sales are $1.3 billion a year when pulp, paper, and sawtimber are added. Other important forest firms are Forestal Bio-Bio, owned by the New Zealand group Fletcher (50,000 hectares); Forestal Millalemu (60,000 hectares); Forestal Monteaguila, owned by Shell (30,000 hectares); and Forestal Copihue (20,000 hectares).

Chilean forestry firms have always had a high level of cooperation. In 1988, they were organized into an association called Forestry Production Group (GPF), coordinated by Fundación Chile, a nonprofit institution formed by the Chilean State and ITT, to promote the development of Chile. Within this initiative, the management of the Chilean forestry firms has changed through the introduction of optimization systems at different decision levels. Most of the systems were developed by the forestry firms in a joint effort coordinated by Fundación Chile. We will describe the systems we developed, the problems we solved, the process we used in developing the systems, the methodology used, its implementation, and finally the results obtained in each case. The systems developed deal with three operational problems: daily truck scheduling, location of harvesting machinery, and short-term harvesting. A typical distribution of operating costs is 30 percent for harvesting, 42 percent for transportation, 14 percent for road building, four percent for loading, and 10 percent for other processes [Weintraub et al. 1996]. The fourth problem the systems deal with is medium-range tactical harvest scheduling, and the fifth problem is long-range strategic planning.

All of these systems have evolved over time as the firms' needs have changed and the systems have become more sophisticated. At the moment, each system is in version 2 or 3. The systems are designed on PCs for ease of use and run in small CPU times consistent with time managers allocate for decision-making meetings. The systems have had an organizational impact. Decision making at each level has relied on these systems, and successful management is seen as associated with the use of these systems.

Use of systems has led to annual savings of at least US $20 million a year. This amount is significant given the size of the firms. For instance, due to the use of three OR systems, Bosques Arauco reports total savings of $8 million a year over a total annual timber production worth $140 million. The firm considers its use of these systems a strategic competitive advantage.

The systems have also had an important impact on management organization and have in some cases contributed to environmental protection. This work has been recognized in other countries: South Africa and Brazil have implemented some of these systems, and New Zealand has expressed interest in them.

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Starting in 1993, a state agency that supports applied research, Fondef, funded the development of basic tools, which were later transfered to forestry firms. This support came through a grant obtained by the group.

The positive impact of these systems has led forestry firms to increase their professional development and training in the use of these quantitative tools. Some of the professionals who directed successful implementations of these systems have been promoted to higher positions within their organizations. As Jorge Serón, CEO of Bosques Arauco, said, "Our firm has been using three systems developed by this group. These systems have had a deep impact on our firm, as they have become basic tools in our forest planning and management. Any new professional we hire is required to learn the use of these systems and make them part of their regular work. This has allowed us to handle a large number of timber stands, multiple products, hauled from many origins to destinations, using 200 trucks with a small number of engineers. In this way, each engineer is capable of managing about 500,000 cubic meters of production per year, leading to a very productive management. Through better use of the harvesting machinery, we reduce erosion. This reduction in environmental harm is vital though difficult to quantify. Overall, I feel that the use of these systems has given us a strategic competitive advantage in the global timber markets, where our firm, which is significantly oriented toward exports, competes in a very competitive setting."

We will comment on the relationship between all the participants in developing these systems: the University of Chile, the forest firms, and Fundación Chile, which coordinated the firms in the Forest Production Group. Their joint development of these systems means that the software has become joint property, evidence of the willingness of the firms in this industry to share technical developments. This willingness exists not only among forest firms within Chile, which could be explained by their need to collaborate in marketing and technological development to compete with other timber-producing countries, such as New Zealand, South Africa, and Canada, but also extends to firms in other countries. Visits of Chilean professionals to forest areas in other countries are common, and a culture of sharing knowledge is far stronger than in other fields. This has made the extension of the systems we developed to multiple firms in Chile, and later to firms in other countries, much easier.

While forest professionals within the firms have become quite proficient in understanding and using the systems, no firm has hired technical personnel in OR. Thus, all systems development depends on the expertise of the university group.

ASICAM: A Truck-Scheduling System

An important problem in forestry operations is deciding how to transport timber each day from different stands (origins or sources), with known supplies, to destinations, such as pulp mills, sawmills, sorting yards, and ports, to meet their daily demands. The timber products transported are characterized basically by the length and diameter of each log. The products available are usually stocks remaining from the previous day plus production throughout the day. Trucks transport loads of logs from origins to destinations. At origins and destinations cranes load and unload the trucks. Although the firms typically subcontract trucks and cranes, they usually organize their schedules. The basic decisions a log-transport manager makes each day concern (1) the origins from which to transport product to satisfy each demand, (2) what trucks and cranes are needed at origins and destinations to satisfy all demands, and (3) the work schedule for each truck and crane.

Besides satisfying demands for products, forestry firms must consider (1) the characteristics of trucks and cranes, basically described by the time and costs involved in trips and in loading and unloading; (2) the arrival time of trucks at destinations, which determines the number of cranes needed for unloading and for coordinating deliveries of logs with downstream operations; (3) the income levels of truck drivers; and (4) the starting and ending points of each truck's daily route.

The basic objective is to satisfy the demand for different products at each destination, while minimizing transportation costs within technical, policy, and labor constraints. A typical forestry firm operates with approximately 10 to 90 origins, five to 30 destinations, and between 50 and 300 trucks. Depending on the distance involved, each truck can make from one to four trips per day. Since transportation costs account for about 40 percent of operating costs, it is important to define and control truck schedules efficiently.

The traditional log-transport systems used in the Chilean forest industry were inefficient and poorly organized. Essentially truck drivers had no well-defined schedules. This led to failures to meet demand, long waiting times in queues, friction among drivers, long working days, low utilization of equipment, and poor coordination with downstream operations, such as the conveyor belt at the mill. In 1988, Bosques Arauco produced 600,000 cubic meters of timber per year, which was transported with a fleet of approximately 90 trucks. Jorge Serón, at the time head of production, and Pier Traverso, head of transportation, worried because truck operations were difficult to handle and expansion plans called for almost tripling production by 1990. They were convinced that their manual scheduling system, based on a magnetic board, could not handle the expansion in volume. That magnetic board was the first effort to organize transportation in the forestry sector. The managers realized the limitations of their manual scheduling, which only allowed them to define rigid trip cycles with schedules that had to be kept for many days and which limited their capacity to respond to variations in production. They needed a new and better tool to improve the efficiency of the operation and to handle the expansion. They were unable to find a system that handled forest-transportation scheduling in high technology countries with forestry sectors, including the USA, Canada, and New Zealand. To improve this situation, they asked the team at the University of Chile, Andres Weintraub, Rafael Epstein, and Ramiro Morales, to develop an administrative and computerized system for Chilean forest firms to program and manage an efficient daily schedule of truck trips. This was the first such joint project of GPF, which was at the time directed by Marcelo Kunz, who is now CEO of Forestal Millalemu.

ASICAM took about a year to develop, but a preliminary version was operative after six months. The system was implemented in January 1989 at Bosques Arauco. Weintraub and Epstein designed the algorithm for ASICAM to be very robust, so that all firms could use it. Later Ariel Schilkrut, who also supported the other systems, participated in maintaining and developing newer versions of the system. Jaime Catalán and Jorge Gatica also contributed to this project.

ASICAM had a dramatic impact on forest transportation. A main reason the project succeeded was that Jorge Serón and Pier Traverso became directly involved in developing and implementing the system and had a clear understanding of the problem and objectives. This close collaboration between academics and managers of the forestry firms was a common factor in the successful implementation of all the systems that we developed. The success of ASICAM showed the potential of operations research tools for forest management.

Eight Chilean firms have implemented ASICAM, and they report savings of 15 to 35 percent of transportation costs.

ASICAM is based on two notions: a centralized administrative system that schedules and controls all trips, and a simulation model for generating such decisions. The administrative overhaul was essential to centralize and coordinate decisions and to schedule trips efficiently. Determining efficient truck schedules is a complex combinatorial problem, which clearly could not be solved well with a manual approach using a magnetic board. We based the computational system on a simulation model driven by heuristic rules that assign trips to trucks. The system, which is run daily, takes the following as its main inputs: the supply of timber products at origins or sources, demands at destinations, truck fleet and crane equipment characteristics, costs and times for the different trips and for loading and unloading, plus an additional set of relevant constraints. As outputs, the system yields requirements for trucks and cranes, a schedule for each, and basic statistics to evaluate performance.

Given the high combinatorial complexity of the problem, we chose an approach that simulates daily operations. We tried to replicate real-time scheduling, given the volumes of products that have to be hauled from origins to destinations and the trucks available. In the simulation process, we assign trucks following specific rules. The simulation starts, for example, at 6:30 AM as the first group of trucks starts loading and later are dispatched to their destinations. As the cranes at origins become available again, new trucks enter the system. After trucks unload at destinations, they are assigned new trips. The system moves along in this manner during the day.

To assign trips in a coordinated way, we chose a moving time horizon of one hour. Given a starting time t_0, the system evaluates all possible trips for all trucks that will become free before $t_0 + 1$ hour. Only those trips that are assigned by the simulation process during the first 15 minutes are actually fixed. Then the starting time moves to $t_0 + 15$ minutes and the trip assignment process is repeated (Figure 1). The assignment of trips is based on evaluating every feasible option a truck has after unloading. An option is a trip to an origin to load a product and another trip to a destination for unloading. An option is feasible depending on truck-frame and engine characteristics, and on policy decisions. These options are evaluated based on priorities and desirability of the trips.

To evaluate the desirability of each feasible trip, we define an index that considers the total real cost plus a congestion penalty. The typical contracts with truck owners link payment with the length of the loaded trips carried out (salaries to truck drivers are managed by the truck owners, not the forest firms). However, the firms realized that in the long run they needed to consider the real costs the truck owners faced (for example, to consider also queuing and empty trips). So the objective was defined to minimize the real costs of transportation. Total real costs faced by truck owners include operational costs (fuel, tires, maintenance) and fixed costs (capital depreciation, insurance, salaries). The penalty for congestion at origins is a heuristic estimate that depends on (1) the trucks that may load at the same time at a given origin, (2) the alternative trips available for those trucks, and (3) the probability of selecting a conflicting trip. The simulation process estimates the congestion effect as it analyzes possible future trips to origins to be made in addition to those already scheduled. The congestion penalty is not a real cost; it is just a device to reflect the loss of efficiency some trip assignments cause to other trucks, and it is not included in the reports.

The selection of the next trip to be assigned is based on the desirability index just described but in the context of trip priorities. Priorities are based on the model's perception of urgency in scheduling trips. Thus, the first priority is for trips to destinations with urgent requirements. For example, if a destination requires four truckloads per hour, and the simulation has assigned only two between 14:00 and 15:00 with few options available to provide the remaining two truckloads, those trips become first priority. The schedule programs efficient trips to minimize transportation costs and reduces queuing at origins and destinations.

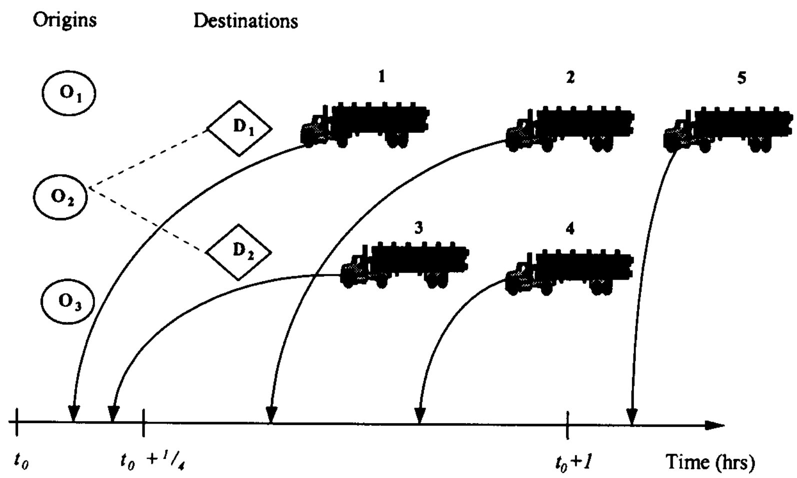

Figure 1: Between t_0 and $t_0 + 1$, trucks 1 and 2 arrive at destination D_1, and trucks 3 and 4 arrive at destination D_2. At t_0 the simulation model assigns a trip for trucks 1, 2, 3, and 4. Decisions for trucks 1 and 3 are performed while decisions for trucks 2 and 4 are released. The simulation time is increased by 15 minutes and the process is then repeated at $t_0 + 15'$. A decision consists of an unloaded trip to an origin and a loaded trip to a destination. For instance, a decision for truck 1 could be loading at origin O_2 and unloading at destination D_2.

Because destinations and downstream operations have limited unloading capacity, arrivals at destinations must be regular. This is not trivial because complete cycles (trip to origin, load, trip to destination, unload) can vary significantly (1.5 to five hours) depending on the locations of the origins and destinations. During the simulation, the system dynamically determines when a destination will be in critical need of supply in order to continue regular operations.

The development and fine-tuning of these heuristic rules took over a year, including tests in different firms. The final algorithm turned out to be robust for all firms and situations. Weintraub et al. [1996], give a detailed description of the system. The system runs on a PC and takes approximately three minutes to find a solution. The operators need to have good knowledge of the transportation system but not a high level of technical preparation. Typically, the operator needs three or four runs of the system to evaluate several scenarios before choosing a solution.

The implementation of the system has provided significant benefits, both quantitative and qualitative. The quantitative improvements have been measured in terms of numbers of trucks, numbers of cranes, operational costs, and total transportation costs. More efficient assignment of trips leads to shorter trips and less queuing. As trucks' productivity increases, fewer trucks are needed (Table 1). This allows a decrease in capital investments. Because the firms usually share the savings with the trucking firms, the trucks that remain in the system have improved the income they produce for their owners. In most cases, reorganizing the administrative system was responsible for a significant fraction of the improvement. As peak arrivals at destinations flattened, the number of cranes needed for loading and unloading decreased by about 20 percent.

Eight Chilean firms have implemented ASICAM, and they report savings of 15 to 35 percent of transportation costs, equivalent to total annual savings of more than $8.5 million a year [Weintraub et al. 1996].

The firms also achieved qualitative improvements, such as improved overall control of the system, by organizing timber stocks at origins, keeping trucks and cranes in good shape, and handling disruptions that occur during the day, and smoother downstream operations by making regular deliveries at demand nodes. In addition, the system has improved the quality of life of workers, reducing their workdays from 14 to 11 hours, and increasing their salaries because of higher productivity. Managers of forestry firms have commented on these improvements [Weintraub et al. 1996]. Claudio Rodriguez, head of the Division of Timber Supply at Forvesa (presently Forestal Mininco), noted, "We have reduced our fleet by 32 percent, but the most positive aspects, in my judgment, are the qualitative benefits concerning people." Bosques Arauco tripled its operations in 1990; Pier Traverso, head of transportation, said in 1992, "ASICAM has been in operation for three years in Bosques Arauco with very significant benefits, which were especially evident when a new plant came into operation. We went from 120 trucks to 300 trucks in a peak month, and in spite of this expansion, there was no chaos, no disorder. In addition, the quality of work of the drivers improved as well as the control over the system, especially with respect to loading and unloading."

Company	Before ASICAM	After ASICAM
Bosques Arauco	156	120
Forestal Millalemu	80	50
Forestal Bio-Bio	118	76
Forestal Río Vergara	120	80

Table 1: The number of trucks four forestry firms required for hauling similar volumes of timber decreased with the implementation of ASICAM.

Leonidas Valdivieso, head of the Department of Harvesting and Transport at Mininco, said, "We have been able to optimize not only transport, reducing the number of trucks, favoring the remaining with more trips, but we have also achieved better coordination between harvesting operations and demand centers." Mauricio Peña from Forestal Millalemu commented, "The most visible and immediate effect was the reduction in the truck fleet from 80 to 50 trucks. Additionally, the number of internal personnel dedicated to programming and supervising transportation was reduced. Further benefits obtained have included the detection of equipment shortages, a reduction of wood stock at origins, and the subsequent decrease in losses due to degradation."

The system has proved to be extremely portable to different realities. For instance, Sawmills Arauco, a subsidiary of Holding Arauco that handles sawtimber production through eight sawmills, has used a version of ASICAM to schedule its truck fleet since 1997. Mondi in South Africa implemented ASICAM; we are developing a version of ASICAM for Aracruz, a large Brazilian forest firm; and according to

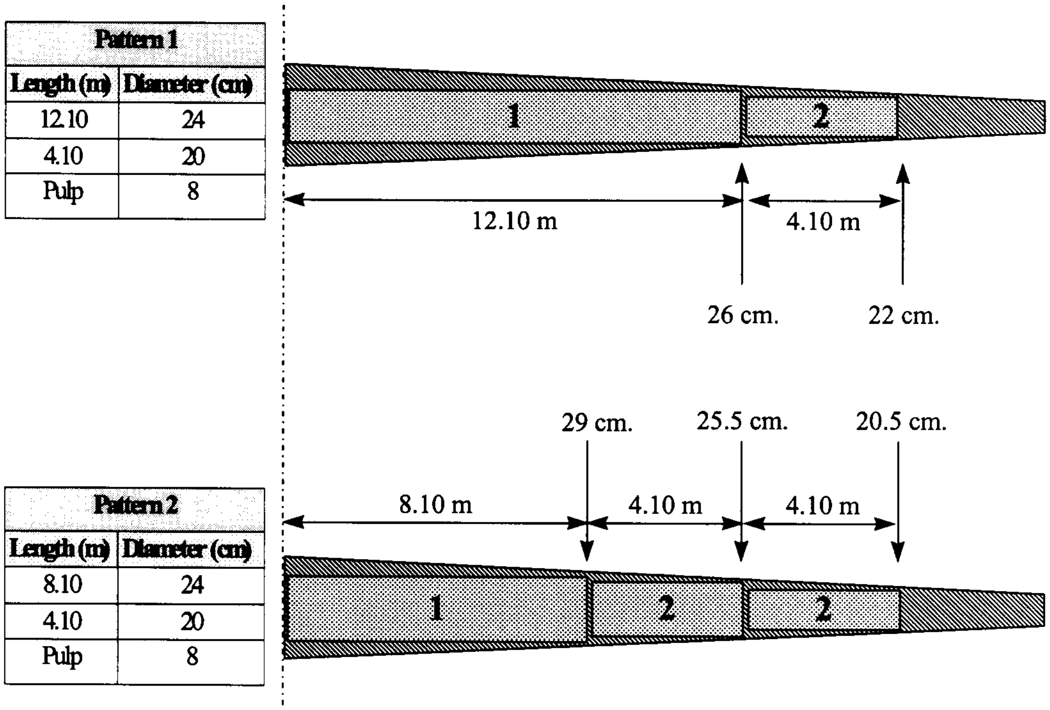

Figure 2: In this analysis of the use of two different bucking patterns, pattern 1 first tries to obtain a piece 12.10 m long and at least 24 cm in diameter. After that, the pattern looks for a piece 4.10 m and 20 cm. Finally, the remainder of the tree goes to pulp. Similarly for pattern 2. The diameters shown in each schematic figure are actual values obtained. Since in pattern 2, at 8.10 m long the diameter obtained (29 cm) is larger than the minimum required (24 cm), the first piece can be cut.

Cossens [1992, p. 18], "ASICAM appears to have good potential for use in New Zealand." (However, it has not been implemented in New Zealand.)

Mondi's implementation of ASICAM required minor modifications to account for the fact that Mondi works around the clock. ASICAM was one of the tools that led to Mondi Forests being awarded the 1996 South African Logistics Achievement Award. As Don Alborough, supplies and logistics manager of Mondi-Natal, explains, "Over a period of years ASICAM was purchased and implemented very successfully into our Natal operations. The control over our and contractor fleet increased dramatically, and Mondi saw doubling of vehicle utilization and a halving of the fleet transporting some 400,000 tons per annum. The system now forms the cornerstone of a quality initiative where it is essential that we feed the merchant mill with a consistent supply of timber with similar properties."

OPTICORT: A Short-Term Harvesting System

After implementing ASICAM, the foresty firms initiated a project to support short-term harvesting. For the purpose of harvesting decisions, forests are divided into reasonably homogeneous stands, similar mainly in tree age, site quality, and management state. Short-term harvest decisions can be viewed as follows: for a period of typically three months, demands for timber products, defined by length and diameter of each piece, are known. At times, the average diameter of all the pieces making up a complete sale is also important. Typical demands are (in order of decreasing commercial value) export logs (long pieces of high diameter), sawtimber (shorter logs of high diameter), and pulp timber (any diameter).

In harvesting, firms use different types of machinery for different types of terrain. They harvest areas with steep slopes using towers or cable logging, and they harvest flat areas using tractors or skidders. When loggers harvest trees they cut them into several products or pieces to respond to demand. This cutting operation is called *bucking.* Bucking can be carried out on the ground and individual pieces are transported to their separate destinations from there, or the whole log can be transported to a sorting center, where the bucking is carried out.

The bucking instructions are given as a set of lengths and diameters to be obtained in sequence, of decreasing diameter and value. Loggers are instructed to obtain as many pieces as possible of each defined piece, in the given order. Thus, from bucking pattern 2 in Figure 2, the logger first tries to get a piece which at 8.10 m has a diameter of at least 24 cm. If at that length the diameter falls below 24 cm, the logger then tries to obtain a piece of length 4.10 m and diameter 20 cm. After that, the rest of the tree is used for pulp, which has a minimum diameter of 8 cm.

Each forestry firm has developed a forest-inventory system based on sample plots, which indicate for each stand and given bucking pattern how much volume can be expected for each product. Figure 3 shows how a sample tree might be visualized by the inventory system before bucking, while Figure 2 shows a schematic solution for two given bucking patterns.

Short-term harvest planning takes into account harvesting and transportation decisions. Transportation costs used in OPTICORT are based on observed-average or estimated transportation costs for different origin-destination pairs. Traditionally, an experienced planner did short-term harvest planning manually. The planner analyzed the demands for different products in the near future (one to three months ahead), the standing timber available in that period, and the firm's capacity for harvesting, which depends mainly on the availability of harvesting equipment (towers, skidders) and trucks for transportation. With this information, the planner scheduled a sequence of stands to be harvested and the machinery to be allocated. The planner defined bucking patterns so as to yield the products needed, including stocks, to satisfy each period's demand, typically a week. The information on standing timber came from preharvest-inventory systems.

Matching standing timber with product demand turned out to be a difficult combinatorial problem, which led to significant losses as mismatches led to harvesting more timber than was really needed and to the degradation of much of the excess. An additional problem, though of lesser impact, was that less than optimal decisions were made in the use of machinery

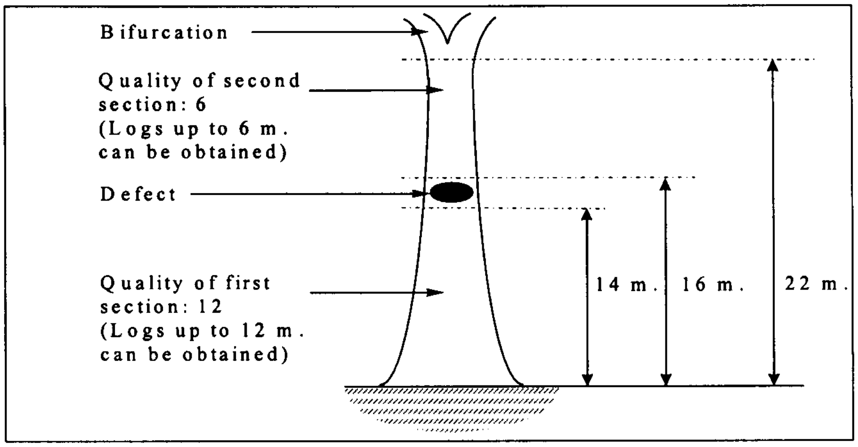

Figure 3: In this representation of simulation criteria in bucking patterns, the bottom part of the tree, below the defect, leads to an export piece, with some residual timber useful only as pulp. The six-meter section above the defect can be used as sawtimber.

and transportation.

OPTICORT seemed a logical way to get better schedules. The development was led by Jorge Serón and Enrique Nieto, head of planning from Arauco. Sergio Alvarez, regional chief, and Eduardo Tapia, a senior manager from Forestal Mininco, also played important roles. Development of the system took about two years, and its implementation at Arauco, Mininco, and Bio-Bio was very successful.

OPTICORT is based on an LP model with a column-generation procedure (appendix). The main decisions the model covers are which stands to harvest among those with mature trees ready for harvesting that are already accessible by existing roads, what type of machinery to use in each operation, what volume to cut each week or period (with the corresponding bucking patterns to be used), and what products should be delivered to different destinations to satisfy demand (stocks can also be accumulated for future use).

A main methodological point was the definition of bucking patterns. The number of such patterns is exponentially high. At first, we built the model with a predefined, moderate set of such patterns for each stand, trying to cover a reasonable range of options. When the model was successfully implemented, we developed a column-generation approach to automatically generate the bucking patterns. This new feature overcame two main drawbacks: first, for users it was too time consuming to generate a "good" set of patterns, and second, the sets of initial bucking patterns were probably missing better options. We based the column-generation scheme on a specially developed branch-and-bound algorithm linked to each firm's forest-inventory system.

The basis of the column-generation scheme is shown in Figure 4. At the root node, the scheme chooses a first cut. For example, it cuts a piece 12.10 m long and 24 cm in diameter. From each node, the scheme defines new branches according to the next cuts that are possible. Thus, after

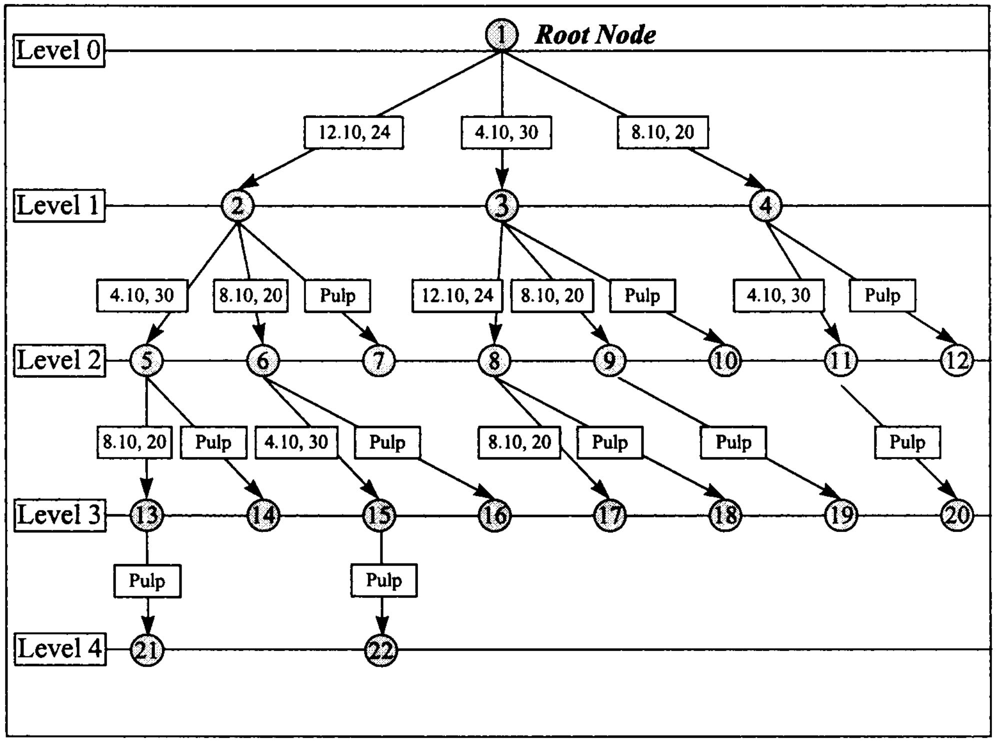

Figure 4: In this branch-and-bound tree for generating bucking patterns, an arc leaving the root node corresponds to the first cut in the bucking pattern (level 0), and a path from the root node to the bottom of the tree represents a bucking pattern. Each arc represents a product defined by length and diameter, while its level indicates the position of the product in the bucking pattern.

a cut 12.10 m long and 24 cm in diameter, a next cut 8.10 m long and 20 cm in diameter is one logical alternative. The value of each branch is defined by the sale value of the corresponding piece, given its length and diameter, and the dual variables of the present solution. Each path from the root node to the bottom of the tree corresponds to a bucking pattern. The scheme, including branching and stopping rules, has been implemented at Bosques Arauco. Tests showed that using column generation improved the objective value by three to six percent over just using a limited number of bucking patterns in the LP model.

The system has been in use since 1991 at Bosques Arauco, Forestal Celco, Forestal Mininco, and Forestal Bio-Bio. They typically run the model about every two weeks, in a rolling horizon of three months. The model runs on a commercial LP code on a PC in about 10 minutes. Quantitative savings, obtained mainly through a better fit of supply of standing timber to demand for specific products, have been estimated at about $3 million per year for the larger firms, and a total of $7.7 million for all firms [Epstein et al. forthcoming]. Using OPTICORT, they make better use of timber to satisfy demand by reducing the amount of timber degradation. The better match has reduced the need for cutting extra volume.

OPTICORT also produced savings in transportation. For instance, Bosques Arauco saved $250,000 per year when the model indicated that it was better to transport directly to destination about 50 percent of the volume that was being transported through intermediate sorting centers. Enrique Nieto, head of planning for Arauco, explains that OPTICORT has been useful in evaluating the overall plan for each season and in estimating the likelihood of satisfying the demand for the remainder of the season. As far we know [Weintraub and Bare 1996], this is the first system developed that optimizes detailed short-term harvesting decisions. We are developing a similar system for Aracruz-Brazil.

PLANEX: A Machine-Location and Road-Design System

The third system deals with the optimal location of harvesting equipment and access roads. Harvesting planners allocate harvesting machinery and design the road network to reach that machinery. When the firm plans to harvest a defined area of 400 hectares in the next three to six months, the planner must decide how to allocate harvesting machinery to most efficiently carry out the harvesting operations. Cable-logging or towers are used for steep areas and skidders or tractors for flat areas. Cable-logging operations, which are more expensive than tractor operations, have longer reach and thus require less road building and hauling. The planner must decide where to place towers and what type of tower to use. Towers typically range from 300 to 1,000 m, with the direction of pull upwards or downwards. Finally, the planner must design roads to access tower landings, where a small, flat area in necessary to store logs and load them into trucks. Also, skidders should work near roads. It is most economical for skidders to work no farther than 300 m from the road. Harvesting operations using skidders and towers and building the access roads account for about 45 percent of the total operating cost, so this is an important problem.

The main decisions in planning are (1) which areas to harvest by skidders and which by towers, (2) where to locate the landings for towers, (3) what area should be harvested by each tower, (4) what roads to build, and (5) what volume of timber to harvest and transport.

In addition, since Chilean forests are mostly in mountainous areas, the design of harvesting systems is complex and must take into account a variety of technical constraints that govern (1) locating the landings for towers according to topographical conditions; (2) locating each tower to comply with its range of reach, depending on the type of tower, operating conditions, and the characteristics of the terrain (for example, ensuring that the reach of the cable for logging is not interrupted by a river); (3) ensuring that topographical conditions permit skidder operations, basically determined by the terrain slope; (4) building roads with appropriate characteristics, including acceptable slope and minimum radius of turn for trucks; and (5) availability of equipment. Cable-logging operations from a specific location are carried out by moving the cable into set positions in a radial sequence, so as to harvest all the timber that is within the reach of the cable and is topographically feasible.

Traditionally, planners allocated machines manually by analyzing topographical maps in a laborious exercise, which allowed the planner to evaluate only a very limited range of options. Jorge Serón of Bosques Arauco led an effort to mechanize these decisions. The best-known systems available were PLANS, developed by the US Forest Service [Twito et al. 1987] and PLANZ [Cossens 1992], a similar system developed for New Zealand. Both interacted with a geographic information system (GIS) and worked basically as simulators. The user defines the location of harvesting machinery on a screen, and the system, based on GIS information, then generates the road to link the machinery with the existing roads and to allocate the timber to be harvested by each machine. Not satisfied with the existing systems, Jorge Serón met with Epstein and Weintraub and asked for a "system to tell me where to locate the towers and skidders and the complete road network."

We developed PLANEX to support these decisions. Arauco senior managers Enrique Nieto and Pedro Sapunar were also heavily involved. Later, Fernando Bustamante and Hugo Musante, senior managers from Bio-Bio and Mininco, respectively, worked on the project for their firms.

PLANEX requires a large amount of information provided by the GIS that each firm has developed, such as altitude-level curves, timber volume, existing road locations and characteristics, and topographic accidents, such as rivers or ravines. There are two main standards for storing geographic data, the raster format, which divides the area into small polygons, usually squares, to which all the information is associated; and the vector format, which stores the data using the exact coordinates of each graphic element (Figure 5). Each has advantages and disadvantages. Managing information is usually easier in raster format, particularly when designing a road. In this case, information that comes from the GIS in vector format is transformed into raster format in cells of 10 $\times$ 10 square meters, to cover topographic conditions, existing roads, and standing timber.

We have developed, jointly with John and Bren Sessions of Oregon State University, a friendly, interactive, graphic user interface that allows the user to visualize and modify solutions. The system incorporates the information from the GIS, plus additional information obtained through the interactive interface regarding possible locations for towers, relevant costs, and such technical parameters as maximum slope for designing roads. The system designs an approximately optimal allocation of machinery based on a heuristic algorithm. The objective of the system is to harvest all volume that is profitable to harvest while minimizing costs. Basic costs considered are installing and operating towers, operating skidders, road building, and transportation, often of little significance given the short distances within the harvesting area.

The system has an internal heuristic algorithm that obtains a solution based on first defining the areas to be harvested with skidders and towers according to slopes. The most attractive locations for installing machinery are then sequentially determined based on a criterion of minimum cost per cubic meter, where costs include harvesting, road building, and transportation. A shortest-path algorithm determines the best new roads to build to link machine locations to existing roads. A local search routine looks for changes of machine locations to improve the solution. Once all locations are defined, a heuristic routine finds a road network of minimum cost.

The machine-location and road-design mathematical problem behind PLANEX can be reduced to an uncapacitated network design (UND) problem (appendix). Moreover, if we discard the transportation cost, which is small compared to the other costs, the problem can be reduced to the well-known Steiner tree problem. The greedy heuristic can be thought of as a dual ascent algorithm, which has proved to be very efficient for solving UND problems [Balakrishnan, Magnanti, and Wong 1989]. We attempted to solve small instances of this UND problem as a mixed-integer LP. To improve the solution speed

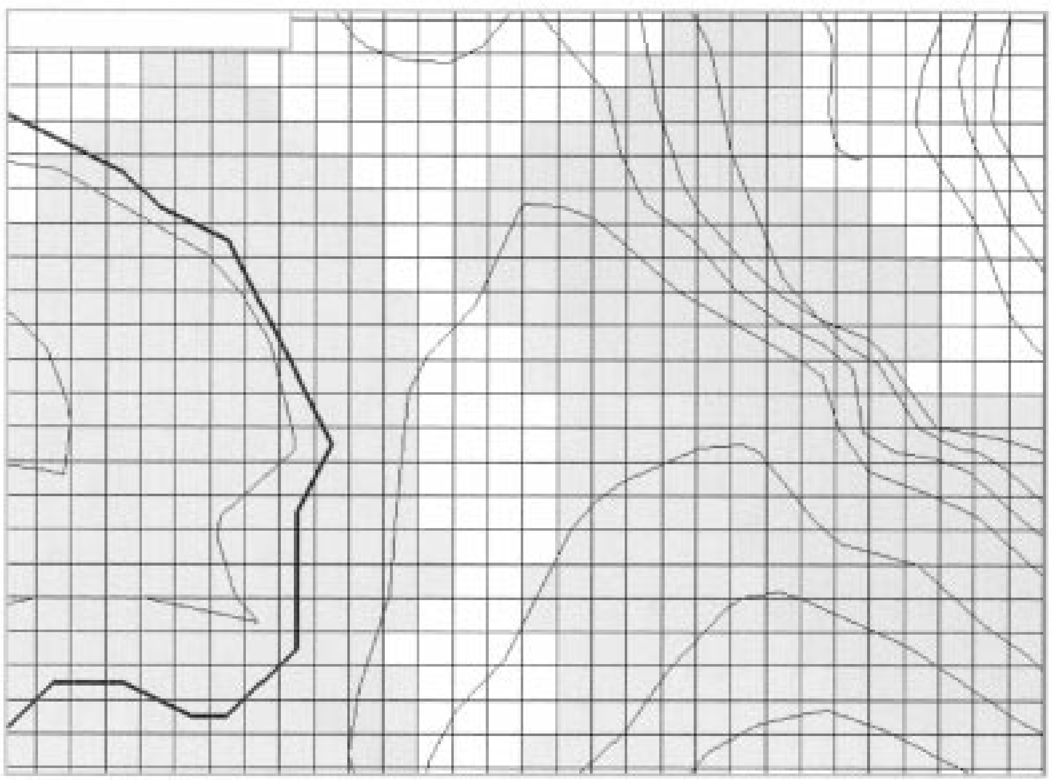

Figure 5: GIS data are stored and presented in raster format or in vector format. The squares represent the raster pixels. The bold line shows a road in a vector format while the thin lines represent isometric altitude curves in vector form. The shaded area represents areas with standing timber in raster form.

of the algorithm, we implemented and tested several options: strengthening the linear relaxation and using Lagrangian relaxation and Bender's decomposition techniques. These exact approaches were not competitive with the heuristic approach, because they required much more CPU time. For real-life large-scale instances, these exact approaches were unable to handle the problems.

"Good harvesting planning will be critical to ensure that harvesting is profitable while environmental quality is maintained."

The system presents the solution in two forms. A graphic menu shows on screen all the relevant aspects of the solution, such as the locations of towers, the areas that are harvested by each tower, the areas harvested with skidders, the areas not reachable or not harvested, new roads, old roads used, and old roads not used (Figure 6). The system generates conventional reports that contain location (coordinates *x-y*) of installed towers, volumes harvested, average costs of harvesting (towers or skidders), road-building cost, and transportation cost.

PLANEX is operated by a forest engineer. With its use, the planner can spend more time analyzing different scenarios instead of generating maps. The graphic interface allows the planner to analyze possible modifications to solutions. Using the mouse on the screen, the user can, for example, choose towers that should be selected or design a road that should be built. The system then optimizes the remaining part of the problem and presents a new global solution. Using this option, the user can analyze different scenarios in a simple and visual way. PLANEX runs on a PC with 128 Mb of RAM memory and needs 15 minutes to solve an instance of 1,000 hectares.

The system has been used since 1996 by Holding Arauco, Forestal Bio-Bio, Forestal Mininco, and Forestal Copihue. Its use has made life easier for planners, and it has led to an improved use of harvesting equipment over previous manual approaches. The companies are still evaluating the quantitative savings. Preliminary estimates from Forestal Bio-Bio suggest savings ranging from 0.5 to 1.5 dollars per cubic meter (Bio-Bio harvests 400,000 cubic meters per year). The experience of Holding Arauco and Forestal Mininco shows gains of 0.5 dollars per cubic meter. Forestal Bio-Bio reported instances in which PLANEX reduced the road network by as much as 50 percent. The cost reduction is due mainly to less road building. These estimates translate roughly into a total annual saving of at least $2 million.

In addition, use of the system benefits the environment because fewer roads lead to less damage during the harvesting process. We believe PLANEX, an interesting application combining OR tools with GIS, is the most advanced system of its kind and the only one that automatically generates a solution to the harvesting problem, indicating the locations of machinery and the road network

OPTIMED: A Tactical Forest Planning Tool

In making tactical decisions, forestry

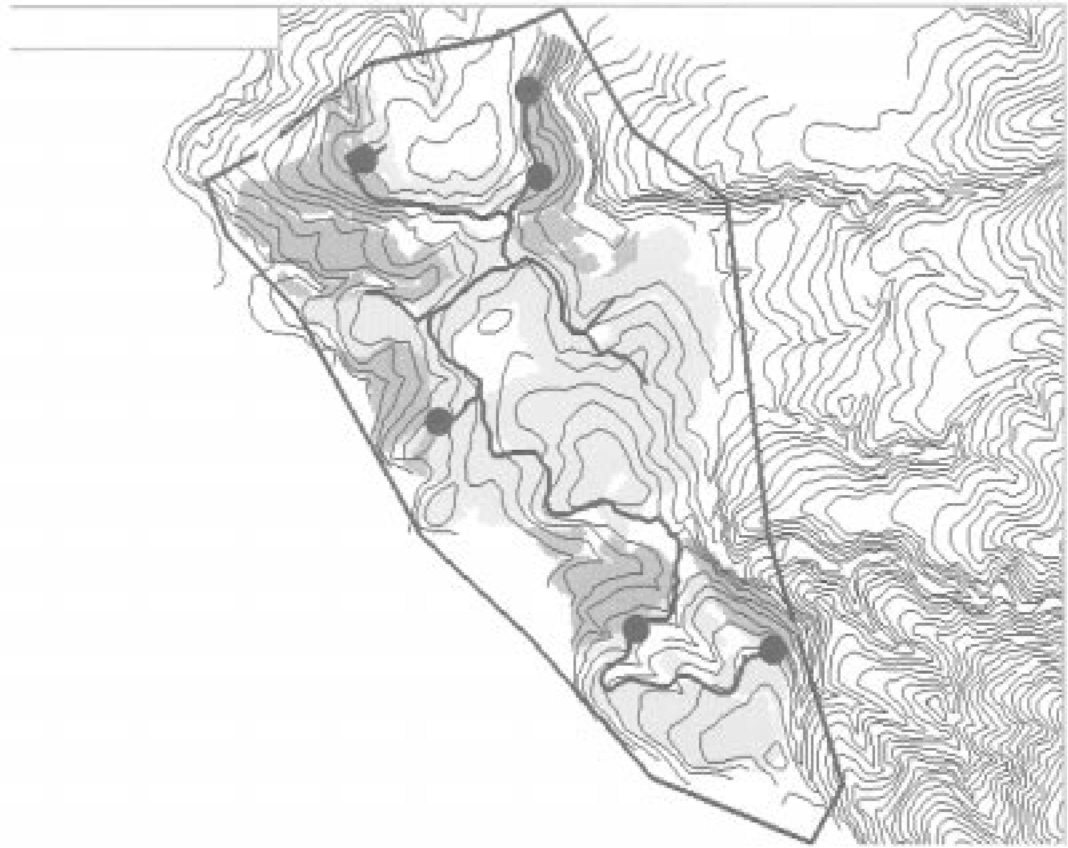

Figure 6: In this PLANEX output example, the light shaded area shows the area harvested with skidders, while the dark shaded area represents tower harvesting. The full lines show the connecting road network, while the black dots indicate the position of the towers.

companies look ahead at two to five years of planning divided into summer and winter seasons. They decide which stands to harvest and in what order, how much timber they will be need to satisfy projected demands, and what roads they will need to gain access to the areas to be harvested. At this level, managers view production in an aggregate form divided into export logs, various classes of sawtimber, and pulp logs. Usually forests are near paved public roads, but firms need to build internal roads. These can either be gravel roads that can be used year round or cheaper, dirt roads that can be used only in the dry summer season. Usually the firms store timber in stockyards during the summer for later use in winter. Each firm has growth-simulation models that estimate timber yields in future periods.

To support these decisions, we developed OPTIMED, a 0–1 mixed-integer LP model. The 0–1 variables correspond to road building or to upgrading road standards from dirt to gravel, and they take into account the fixed costs of harvesting operations. We handle fixed costs by requiring that any harvested tract be of a certain minimum area. This model is similar to models the US Forest Service developed for long-range planning [Kirby, Hager, and Wong 1986; Weintraub et al. 1996]. Solving this mixed-integer LP model poses difficulties because of road-building variables. To overcome this disadvantage, we need a combination of schemes, including strengthening the LP formulation and heuristic rounding off of variables. The model runs on a PC using a commercial LP code and takes about 30 minutes for a typical run. Lagrangian relaxation was useful in some cases but was not implemented for the users. Monique Guignard of the University of Pennsylvania collaborated with us in developing the algorithms. Andalaft et al. [1998] describe the model and its solution approach in detail.

Marcelo Kunz at Millalemu first suggested the development of a tactical planning system. Alexis Wainer, regional manager for operations, and Cesar Lagos, a senior manager, worked very closely with the academic group in developing the system. Forestal Millalemu has used OPTIMED regularly since 1994, running it every few months. Improvements in this case are difficult to estimate because of the long planning horizon, but it does help the firm to make better use of standing timber. Alexis Wainer, regional head at Millalemu, estimates revenue gains of about $200,000 per year from improvements in this area.

In addition, Millalemu has used OPTIMED to evaluate the purchase of land with mature timber, an option large forestry firms frequently face. Once a forest is offered, Millalemu incorporates its stands into the model. The difference in net benefit between runs with and without these stands indicates their value to Millalemu. Because of transportation costs, the location of these potential timberlands is important. Also, tree age may make a stand of timber more valuable to one firm than to another. A firm with a shortage of mature trees will have more urgent need of timberland purchases to satisfy product demand. We are developing a tactical-planning tool, somewhat similar to OPTIMED, for Aracruz, Brazil.

MEDFOR: A Strategic Planning Tool

MEDFOR deals with long-range strategic decisions, in a typical horizon of 50 years, which corresponds to two forest rotations. The model is designed to support decisions on the sustainable production of timber through the planning horizon, maintaining a consistent supply for the industrial plants (mainly sawmills and pulp plants), and to estimate the volume of log exports, to select silviculture regimes for plantations, to establish policies for the purchase, sale, and rental of timber lands, and to project cash flows. The main problem is to maintain a consistent relationship over time between timber availability and demands from sawmills, pulp plants, and export opportunities.

The model was developed by Ramiro Morales. Simon Berti, CEO of Forestal Bio-Bio, Mariana Lobel, senior manager of Forestal Bio-Bio, and Carlos Granier, senior manager of Cholguan, participated in developing and implementating the system. The model considers both data and decisions in a very aggregate form and is a moderate-sized LP model. It is run several times a year. An important aspect in defining the model is the process of aggregation, in which stands with similar characteristics (site quality, tree age, density of planting, geographical location) are grouped into macro-stands and timber products are grouped into export, sawmill, or pulp type. Information on future yields is obtained through inventory-growth simulators. Costs, revenues, and technical production coefficients corresponding to these aggregate activities must be estimated with care. It is difficult to evaluate quantitative gains obtained from the use of the system, given the very long-range planning horizon. Simon Berti estimates savings of between $2.5 and $5.0 million a year due to better use of the timber.

The system is being used successfully by Forestal Bio-Bio and Cholguan and partially by Masisa. We are currently implementing a similar model for Aracruz, Brazil. It explicitly includes industrial-plant decisions, such as building, expanding, and closing processing installations, in a mixed-integer LP model.

Conclusion

These five systems have had a profound organizational impact on the forestry firms and have led to savings the firms estimate to be at least $20 million annually. We feel that ASICAM, OPTICORT, and PLANEX, in particular, have been pioneering efforts in the forestry-management field. We continue to collaborate with the forestry firms to enhance these systems by including additional management options and improving the user interface. The systems OPTIMED and MEDFOR have not been used extensively in the industry, because the large firms had established systems for dealing with these problems.

In addition to the present implementations in Chile, South Africa, and Brazil, we are planning a joint venture with the Forest Research Institute (FRI) of New Zealand to combine PLANEX, our machine-location system, with MARVL, a New Zealand advanced inventory system. As Bruce Manley, portfolio manager at FRI, explains, "Good harvesting planning will be critical to ensure that harvesting is profitable while environmental quality is maintained. Consequently I anticipate that PLANEX will have great applicability for harvest planning in New Zealand. I also believe that there are real opportunities for linking PLANEX in with our MARVL preharvest inventory system, with environmental data, and with harvesting cost information to provide an integrated harvest planning system." Interest in some of these systems has also been expressed in Canada, Zimbabwe, and Colombia.

Chile is now structuring more stringent environmental controls for implementation in the near future. There is an obvious economic cost in implementing environmental protection measures, such as costs associated with avoiding the use of heavy machinery on fragile soils to limit erosion or avoiding harvesting near river banks to limit water sedimentation. The impact of these controls is typically reflected in an increase in harvesting costs or in a decrease in harvested timber. One present line of development, started in 1997 and supported by the forestry firms and a grant from Fondef, is to modify our models to evaluate the trade-offs between these costs and environmental protections to support the political discussion on these issues. Once the government has defined environmental protection rules, we will incorporate these environmental protection constraints into the systems that support the planning processes of the forestry firms, allowing them to comply with the rules in an optimal way.

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APPENDIX

Mathematical Formulation of the Short-Term Harvesting Model

We show a simplified version of the model solved by OPTICORT.

Parameters

VOL_i: Volume available in stand i (m^3).

REN_{ijk}: Fraction of product k obtained per each cubic meter bucked using bucking pattern j in stand i.

DD^{min}_{ktd}, DD^{max}_{ktd}: Minimum and maximum demand for product k in period t at destination d (m^3).

DI_{dt}: Average diameter required at destination d in period t (cm).

DM_k: Diameter of product k (cm).

CAC_t: Production capacity in period t (m^3).

PV_{dk}: Sale price for product k at destination d ($).

$COST_i$: Cost of harvesting in stand i ($\$/m^3$).

CTA_{idk}: Transportation cost for product k between stand i and destination d ($\$/m^3$).

Variables

Y_{idkt}: Volume of timber transported from stand i to destination d, of product k in period t (m^3).

K_{ijt}: Volume of timber produced in stand i using bucking pattern j in period t (m^3).

Objective function

$$\text{Max} \sum_{i,d,k,t} (PV_{dk} - CTA_{idk})\, Y_{idkt} - \sum_{i,j,t} COST_i K_{ijt}.$$

Constraints

(1) Total volume harvested is bounded by existing timber.

$$\sum_{j,t} K_{ijt} \leq VOL_i \quad \text{for all } i.$$

(2) Timber harvested is bounded by production capacity.

$$\sum_{i,j} K_{ijt} \leq CAC_t \quad \text{for all } t.$$

(3) Volume transported is bounded by production of each product in each stand and period.

$$\sum_j REN_{kij} K_{ijt} - \sum_d Y_{idkt} \geqslant 0 \quad \text{for all } i, k, t.$$

(4) Demand must be satisfied for each product at each destination during each period.

$$DD^{min}_{ktd} \leqslant \sum_i Y_{idkt} \leqslant DD^{max}_{ktd}$$

for all k, d, t.

(5) For the set of products at destination d in period t, a minimum average diameter must be satisfied.

$$\sum_i \sum_{k \in s} DM_k Y_{idkt} \geqslant DI_{dt} \sum_i \sum_{k \in s} Y_{idkt}$$

for all d, t.

(6) Nonnegativity.

$$K_{ijt} \geqslant 0,\ Y_{idkt} \geqslant 0 \quad \text{for all } i, d, k, j, t.$$

The actual model is more complex. For example, the model considers the use of different types of harvesting machinery, the grouping of neighboring stands for transportation purposes (this significantly reduces the size of the model), and the constraining of the supply to ensure that a specific demand is regular over several periods (a shipment for export for example).

A cost of standing timber, which is not a financial one, is added to the objective function to avoid nearsighted solutions, in which more valuable trees could be harvested to save, for example, on transportation costs. While this would improve the short-term profits, it would decrease the value of the firm in the long run.

The Scheme for Generating Bucking Patterns

Given the solution to the LP problem, with a given set of bucking patterns, new bucking patterns are defined as follows. In the LP model, constraints (1), (2), and (3) involve bucking patterns. Let γ_i, δ_i, and β_{ikt} be, respectively, the dual variables of constraints (1), (2), and (3). Then the reduced cost of a bucking pattern variable K_{ijt} will be

$$\bar{C}_{ijt} = \gamma_l + \delta_t - \sum_k \beta_{ikt} REN_{kij} - COST_i.$$

We need to find bucking patterns with value $\bar{C}_{ijt} > 0$ to improve the current solution. Note that bucking patterns are generated for each stand and period. If we define

$$\alpha_{it} = \gamma_i + \delta_t,$$

the dual variables α_{it} represent the value assigned to one cubic meter of a mix of products already defined for stand i in period t, while β_{ikt} represents the value of a cubic meter of product k obtained in period t in stand i.

To generate improving patterns, we developed a branch-and-bound algorithm as shown in Figure 4 in the text. In the branch-and-bound tree, in each branch, the length and minimum diameter of a product is defined. For example, branch 1–2 defines a product of length 12.10 m and minimum diameter 24 cm.

The value at each node is determined by the addition of the values of each branch leading to that node, that is, the value of node 14 is defined by the value of products (12.10,24 / 4.10,30 / pulp). The yields of each product are determined by the preharvest-inventory system. Suppose the yields for node 14 in the example have proportions (50%, 30%, 20%), then for given dual values β_1, β_2, β_3 for these three products and a for the corresponding stand, all in period t, the value of node 14 will be

$$\alpha - 0.5\beta_1 - 0.3\beta_2 - 0.2\beta_3.$$

The column-generation feature was implemented mainly by Jaime Gabarró and Philippe Chevalier. The rules for branching and bounding are described by Epstein et al. [forthcoming]. The search with this column-generation scheme can be carried on to optimality or stopped after a number of improving patterns have been found. Figure 7 shows the variation in objective value in a test problem for two strategies: the column generation carried on to optimality or stopped after three improving patterns are found.

Mathematical Formulation for PLANEX

We show a mathematical model formulation for the problem behind PLANEX.

Parameters

V: Set of pixels or points in the study area, as shown in Figure 5.

E: Set of road links in the form (i,j) where i and j are pixels of V.

$X \subset V$: Set of exit points. We consider the timber to be outside the study area when reaching one of these points. One of the exit points is a dummy pixel to which we send timber that is not worth harvesting.

Q: Set of machine types.

T^q: Total harvesting capacity of machine type q.

$G_i^q \subset V$: Set of pixels that can be harvested from pixel i with a machine type q.

v_i: Timber volume on pixel i.

$D = \sum_{i \in V} v_i$: Total demand on the study

area.
c_e: Fixed cost of building link e.
a_i^q: Fixed cost of locating a machine type q on pixel i.
b_e: Transportation cost, per cubic meter, on link $e \in E$.
g_{ij}^q: Cost, per cubic meter, of harvesting pixel j from pixel i using machine type q.
Variables
x_e: 1 if link $e = (i,j)$ is built, 0 otherwise.
y_i^q: 1 if machine type q is located on point i, 0 otherwise.
w_{ij}^q: Timber volume harvested on pixel j from pixel i using machine type q.
f_e: Timber flow on arc $e = (i,j)$.
s_i: Timber exiting the forest at pixel $i \in X$ ($s_i = 0$ for all $i \in V \backslash X$).
Objective function

$$\text{Min} \sum_{e \in E} c_e x_e + \sum_{q \in Q} \sum_{i \in V} \sum_{j \in G_i^q} g_{ij}^q w_{ij}^q + \sum_{q \in Q} \sum_{i \in V} a_i^q y_i^q + \sum_{e \in E} b_e f_e$$

Constraints
(1) Flow balance constraint at each pixel.

$$\sum_j f_{ji} - \sum_j f_{ij} + \sum_q \sum_j w_{ji}^q = s_i \quad \text{for all } i \in V.$$

(2) All the timber must be harvested. A dummy exit point represents the unreachable or uneconomical harvesting pixels.

$$\sum_{i \in X} S_i = D.$$

(3) To harvest pixel j from pixel i using a machine type q, we have to locate such a machine on the pixel.

$$w_{ij}^q \leq v_j \, y_i^q \quad \text{for all } i, j \in V, q \in Q.$$

(4) The harvesting is bounded by the timber supply of each pixel.

$$\sum_q \sum_i w_{ij}^q \leq v_j \quad \text{for all } j \in V.$$

(5) Each machine type has a maximum volume capacity.

$$\sum_i \sum_j w_{ij}^q \leq T^q \quad \text{for all } q \in Q.$$

(6) To carry timber on a link, we have to build the link beforehand.

$$f_e \leq D x_e \quad \text{for all } e \in E.$$

(7) Nonnegativity and integrality of the decision variables.

$$x, y \in \{0,1\} w, f \geq 0.$$

In this formulation, since the road ca-

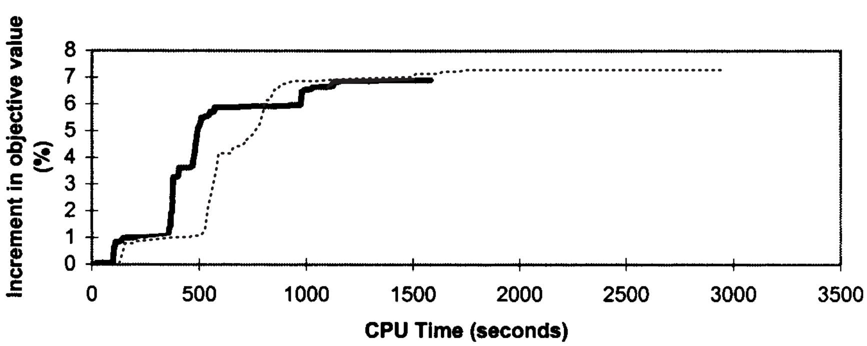

Figure 7: The pattern generation approach produces improvements on the objective function value. The full line represents increments in the objective value when the column-generation scheme is stopped after three improving patterns have been found. The dotted line shows results when the column-generation scheme is run to optimality. The solutions show steep improvements at some iterations followed by a number of iterations with negligible improvement. The approach of stopping the column-generation scheme when three improving patterns are found appears superior.

pacity D defined in constraint (6) is never exceeded (D is the total timber to be harvested), the problem corresponds to an uncapacitated-network-design probem.

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