Country-wide and regional wood volume regulation with a harvest scheduling decision-support system

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Abstract

As part of the development of a decision-support system for integrated harvest scheduling and wood allocation in Coillte (The Irish Forestry Board), a number of studies were carried out with the objective of evaluating the capabilities and flexibility of a prototype system, the Harvest Scheduling System (HSS), developed by Williamson (1991). Of a total of five studies carried out, two are reported in this paper. The first was used to analyse periodic, fluctuating volume constraints. The results indicated that the demand by management for regulated regional harvest volumes had a significant negative impact on overall profits. Hence, the need for regional volume regulation should be assessed. The second of the two studies indicated that it was possible to produce a periodic, increasing supply of wood in each region. However, this resulted in a large reduction in profits, irrespective of the level of annual increase imposed. The relevance of this type of regulation in relation to sustainability and to the expanding wood processing sector should therefore be carefully examined. The results of the two studies illustrated that the HSS can provide valuable decision-support to Coillte managers at national and regional levels.

Keywords: harvest scheduling, volume regulation, decision-support system, constrained optimisation.

Introduction

Coillte (The Irish Forestry Board) is the largest forest landowner in Ireland. By the end of 1995, the Board owned 390,000 ha of forest estate (Department of Agriculture, Food and Forestry 1996). The estate is scattered in nature and comprises 117 forests, 5,600 different properties and 125,000 sub-compartments or stands. It has an unbalanced age class distribution due to large planting programmes over the past 20 years (Carey 1997). The Coillte wood supply is forecasted to grow from 2.2 million m^3 in 1997 to 3.8 million m^3 by 2010. If target planting levels (Department of Agriculture, Food and Forestry 1996) are achieved national wood production (including Coillte and the private sector) is predicted to grow to about 10 million m^3 by 2030. This increased wood volume and the more wide-ranging requirements of the expanding processing sector of the Irish forest industry have made current planning procedures inadequate. Traditionally harvest scheduling has been conducted in isolation from wood allocation and optimisation techniques have not been used. The production of an efficient and cost effective harvest schedule that takes into account forest management constraints, processing sector requirements and the location of the demand and supply, has become an extremely difficult task.

To facilitate the management of these increased and more complex wood flows efficiently and effectively, new integrated management procedures such as a Harvest Scheduling System are required. Currently a Harvest Scheduling System (HSS), incorpo-

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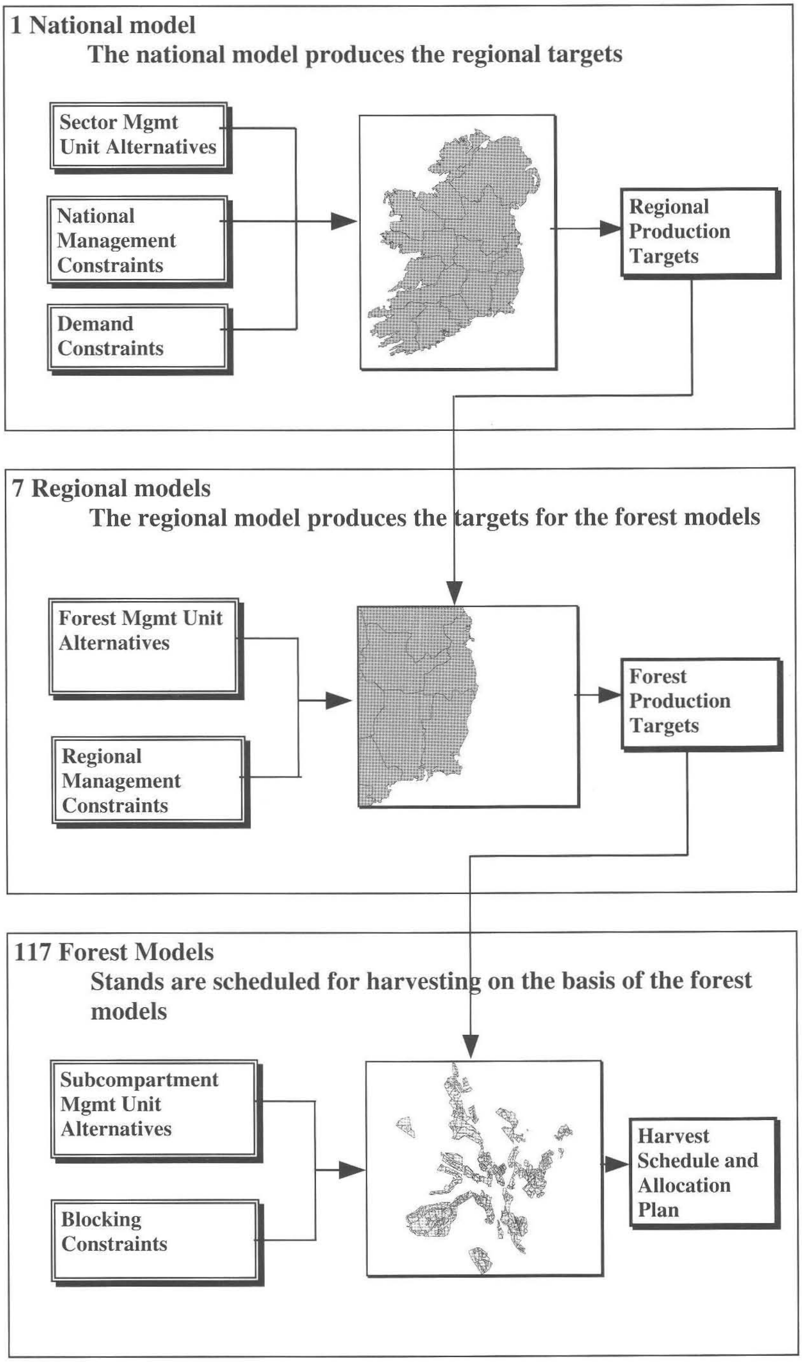

Figure 1. *Schematic diagram of the hierarchical model structure.*

rating wood allocation procedures, is being evaluated as a decision-support tool. To improve Coillte's current methods of determining wood production targets and their subsequent allocation, a number of problems were addressed in the developed HSS. First, the processing sector demand was included, to change the emphasis from a production- to a demand-driven approach. Second, the spatial distribution of market demand and wood supply, and the associated haulage cost was included in the production target determination process. Third, the economic consequences of selecting a particular production year for a particular stand were evaluated with respect to value increment and harvesting and transport costs. In addition, the HSS provided the manager with an optimal solution, whereas, in the past, the production of a stand harvest schedule was a 'trial and error' process.

The full operational procedures of the HSS can be divided into five modules. These are: management option production, growth simulation, data aggregation, optimisation and report generation modules. A three-level hierarchical model was used in the development of the present wood harvest scheduling system (Williamson 1991). It consisted of a national level model, seven regional level models and 117 forest level models (Figure 1). The national model determined optimal regional production targets, which satisfied both the requirements of the processing industry and national, regional and forest management constraints. The targets that were produced in the national model were used to run the seven regional models. (Coillte reduced the number of regions from seven to six at end of 1997. The HSS was developed prior this reorganisation. However, the model can easily be modified to incorporate this change.) Each region produced optimal production targets for each forest within that region. A forest level model was produced for each of the 117 forests. The targets that were produced in the regional models were used to produce a stand (sub-compartment) harvest schedule for each forest.

Examples of operational optimisation-based forest management decision-support systems

A large number of planning models have been developed internationally over the past twenty years to aid decision making in forest management. While many of these are of interest, only a few such as 'MELA', 'FOLPI', 'LOGPLAN' and 'REGRAM' have found widespread use. Each of the models uses linear programming (LP) techniques. LP models consist of a (linear) objective function, expressing the alternative courses of action, and a set of (linear) constraints, expressing limitations on resources and on acceptable scenarios. As a result of the increased computing power, LP models can be constructed and solved at almost any scale and level of precision. The most important restriction on size and complexity is the capability of the modeller to visualise the complex interactions embedded in the models (Nieuwenhuis 1989).

MELA is a forestry model and an operational decision support system that integrates stand management planning and forest wide production planning into a single hierarchical optimisation problem (Siitonen 1995). MELA was originally designed in the 1970s for regional and national analysis of wood production potentials in Finland (Siitonen *et al.* 1996). Large-scale applications of MELA include two rounds of national wood production analysis in Finland since the middle of the 1980s (Siitonen 1993).

FOLPI (Forestry Oriented Linear Programming Interpreter) is an LP based forest estate modelling system developed by Garcia (1984). FOLPI was designed to be compatible with the Interactive Forest Simulator (IFS), as it was considered that growth simulation and LP are complementary. The IFS (Garcia 1981) was widely used by the New Zealand Forest Service. FOLPI is an optimising, forest estate modelling system that allows a forest manager to evaluate alternative management strategies for the forest estate (Manley and Wakelin 1990). Applications of FOLPI include yield regulation, forest management and investment evaluation, forest valuation and log allocation (Manley and Threadgill 1990, 1991).

LOGPLAN is an LP model that was developed to aid in the construction and evaluation of one year logging plans (Newnham 1975). The objective of the model is to obtain a plan that will satisfy mill demand throughout the year at a minimum cost, while satisfying constraints on available wood and machine resources. Newnham (1991) also developed LOGPLAN II, which can be used to formulate annual operating plans for companies.

In New Zealand REGRAM I (Regional Resource Allocation Model) uses a combination of LP and simulation techniques. Tasman Forestry Ltd. have used REGRAM I since 1991 as the company's principal resource planning tool (McGuigan and Scott 1995). The system is capable of being run as a simulator, an optimiser or a combination of both. Tasman Forestry have used REGRAM I to optimise thinning and clearfelling in a number of forests in a given region, to determine the availability of resources from external suppliers, to allocate resources between processing plants and to define planting and regeneration strategies (McGuigan 1992).

Williamson (1991) developed the HSS prototype that is used in this study. The HSS has been formulated within the framework of LP and mixed integer programming (MIP) to optimise solutions. The national and regional level models are based on linear programming, while the forest level models use mixed integer programming. The HSS is linked to ARCINFO (Geographic Information System) which extends the analysis and interpretation capabilities of the HSS and combines the output with existing information systems. The system was initially developed to help optimise the allocation and transportation of Coillte's annual wood supply of 1.4 million m^3 in 1990. The actual wood allocation and haulage routes were compared with the optimal routes suggested by the study (Williamson and Nieuwenhuis 1991, Nieuwenhuis *et al.* 1991, Nieuwenhuis *et al.* 1992). The programme indicated that a 38% reduction in overall transport costs was possible (Williamson 1991). The HSS was further developed using inventory and forecast data for a time span ranging from 1994 to 1998 (Williamson and Nieuwenhuis 1994, Nieuwenhuis and Williamson 2000).

Evaluation of the HSS

The evaluation process of the HSS began in January 1997. Coillte supplied up-to-date inventory data and a forecast of wood production for the period 1998-2002. This forecast was used to compile the management constraint files. Constraints were used to control the level of production. These can be applied at national, regional or forest level. Within each level, constraints can be applied to volume, revenue and area. For the purpose of this study only volume constraints were used. Volume constraints can be applied to total volume, to products (pulp, pallet and sawlog), harvest type (first, second and subsequent thinning, clearfell) or species. The introduction of (additional) constraints or making existing constraints more restrictive will always result in an optimal solution with a value less than or equal to the original. The HSS optimises the Net Present Value (NPV) of harvest revenues, using a discount rate of 5%.

The following studies have been carried out with a view to evaluate the HSS (Nugent 1998):

1. A 'no constraints' study: the objective was to see what the maximum NPV and the associated NPV/m^3 was that could be attained where no management constraints were applied.
2. Models that conform to Coillte's harvest forecast: the objective was to see if the HSS could produce a forecast in line with Coillte's harvest forecast and to determine the associated decrease in NPV and NPV/m^3 as compared with the 'no constraints' study.
3. Periodic fluctuating volume constraints: the objective was to produce an even supply of volume from year to year within each region and to determine the associated decrease in NPV and NPV/m^3 as compared with the 'no constraints' study.
4. Periodic increasing volume production models: the objective was to create an increasing supply of volume from year to year, within each region and to determine the cost of imposing these constraints when compared with the 'no constraints' study.
5. Regional study: The objective was to produce a harvest schedule for Coillte's southern region.

Studies 1 and 2 have been reported in Nieuwenhuis and Nugent (2000). The main conclusion was that Coillte's production smoothing process resulted in harvesting schedules that were not feasible, as no adjustments for volume were included. In this paper, studies 3 and 4 are presented. For each study, a comparison with the output of study 1 is also included.

Methods

Periodic fluctuating volume constraints (study 3)

In this study the objective was to produce an even supply of volume over the planning period within each region and to determine the associated impact on net revenue as compared with the 'no constraints' study. Constraint files were added to the 'no constraints' study. Explicit constraints were compiled whereby the maximum fluctuation of the HSS volumes from Coillte's harvest forecast was set at ± 10%, ± 5%, ± 3%, ± 2% and ± 1% (as in study 2). These constraints were applied at national level only and ensured that a steady supply of wood was achieved while meeting Coillte's targets. Implicit constraints were used to limit the maximum volume fluctuation from year to year within each region to ± 10%, ± 5%, ± 3%, ± 2% and ± 1%. For example, the volume produced in 2000 could fluctuate by ± 10%, ± 5%, ± 3%, ± 2% and ± 1% on the volume produced in 1999. These constraints were applied at a regional level and ensured managed regional total supply patterns. For each constraint file a national model, seven regional models and some forest models were solved and analysed.

Periodic increasing volume production models (study 4)
Constraint files were compiled and added to the 'no constraint' model. Explicit constraints were compiled, whereby the maximum fluctuation of the HSS volumes, compared to Coillte's harvest forecast, was set at ± 5% and ± 1% (as in study 2). These constraints were applied at national level only, i.e. total volume constraints. Implicit constraints were used to specify that the harvest volumes in each region should increase by a minimum of 1% or 5% in each year of the planning period, depending on the constraint file used. These constraints were applied at a regional level only.

Results

Periodic fluctuating volume constraints (study 3)
The ± 10% fluctuation model
The periodic volumes harvested within each region were set to vary by a maximum of ± 10%. In addition, the fluctuation of the HSS national-harvest volumes from Coillte's forecast was set at ± 10%. A relatively even volume production was achieved within each region in this case (Table 1). The NPV obtained from this national model was IR£303.1 million. The cost of applying these constraints represented a decrease of 10.1% by comparison with the NPV obtained in the 'no constraints' study (see Table 6 for a summary of the results). The volume harvested decreased from 15.5 million m^3 to 15.2 million m^3 and the NPV/m^3 was reduced from £21.72 to £19.98, a decrease of 8.0%.

Table 1. *Regional production volumes which are within the annual volume fluctuation of ± 10%.*

Year	*1*	*2*	*3*	*Region* *4* *m^3*	*5*	*6*	*7*	*Total*
1998	418,005	455,395	532,699	349,802	376,204	498,297	369,604	3,000,006
1999	459,802	409,865	479,429	384,775	413,820	457,303	395,006	3,000,000
2000	505,783	378,908	431,487	423,257	416,669	411,567	432,324	2,999,995
2001	556,357	416,804	388,341	465,585	375,000	370,418	471,908	3,044,413
2002	611,994	458,477	349,503	512,141	357,722	333,371	503,988	3,127,196
Total	2,551,941	2,119,449	2,181,459	2,135,560	1,939,415	2,070,956	2,172,830	15,171,610

The periodic percentage changes in volume production that occurred varied within each region (Table 2). Regions 1, 3 and 4 were limited at each interval by the ± 10% constraints used in this model. For example, the periodic volume produced for region 1

Table 2. *Periodic change in volume within each region for the ± 10% fluctuation model.*

Period	*1*	*2*	*3*	*Region* *4* *%*	*5*	*6*	*7*
1998-1999	10.0	-10.0	-10.0	10.0	10.0	-8.2	6.9
1999-2000	10.0	-7.6	-10.0	10.0	0.7	-10.0	9.4
2000-2001	10.0	10.0	-10.0	10.0	-10.0	-10.0	9.2
2001-2002	10.0	10.0	-10.0	10.0	-4.6	-10.0	6.8

increased by 10% each year which was the maximum volume increase allowed for by the model.

The ± 5% fluctuation model

In this scenario, the difference between the HSS and Coillte's national harvest volumes, and the periodic volumes harvested within each region were set to vary by a maximum of ± 5%. This resulted in a more even supply of wood for each region (Table 3). A comparison of the preceding model and the ± 5% fluctuation model showed that the NPV and the NPV/m^3 were reduced (Table 6). The total volume harvested decreased from 15.2 million m^3 to 15.0 million m^3 when compared with the previous model.

Table 3. *Regional production volumes which are within the annual volume fluctuation of ± 5%.*

				Region				
Year	*1*	*2*	*3*	*4*	*5*	*6*	*7*	*Total*
				m^3				
1998	399,004	434,696	536,549	333,899	359,102	475,648	352,805	2,891,703
1999	418,949	456,437	527,089	350,590	377,055	499,433	370,436	2,999,989
2000	439,904	433,612	500,741	368,127	395,907	474,455	388,962	3,001,708
2001	461,889	419,393	475,700	386,531	415,704	450,739	408,412	3,018,368
2002	484,987	440,361	451,916	405,859	436,492	456,009	428,831	3,104,455
Total	2,204,733	2,184,499	2,491,995	1,845,006	1,984,260	2,356,284	1,949,446	15,016,223

It was evident that the regional fluctuations within each period were reduced. This resulted in a more uniform wood harvest forecast. For example, the difference in the volume to be produced in region 1 between 1998 and 1999 was forecast at 19,945 m^3 or 5% of the 1998 volume (as compared with 10% volume fluctuation in the previous model). The periodic percentage change in volume production that occurred within each region was quite uniform except for regions 2, 3 and 6 (Table 4). Regions 1, 4, 5 and 7 were limited at each interval by the ± 5% constraints.

Table 4. *Periodic change in volume within each region for the ± 5% fluctuation model.*

				Region			
Period	*1*	*2*	*3*	*4*	*5*	*6*	*7*
				%			
1998-1999	5.0	5.0	-1.8	5.0	5.0	5.0	5.0
1999-2000	5.0	-5.0	-5.0	5.0	5.0	-5.0	5.0
2000-2001	5.0	-3.3	-5.0	5.0	5.0	-5.0	5.0
2001-2002	5.0	5.0	-5.0	5.0	5.0	1.2	5.0

The ± 3% fluctuation model

Subsequently the ± 3% fluctuation model was solved and analysed. As in the case of the ± 5% model, the results showed a further reduction in the NPV and the NPV/m^3 (Table 6). The total forecast volume available for harvest was reduced from 15.0 million m^3 in the ± 5% model to 14.8 million m³, as a result of the more restrictive fluctuation constraints in this model. It is evident that the regional volume fluctuations within each period have been reduced, and a smoother forecasted wood harvest over time resulted. The resulting periodic percentage changes in the volume production forecast (Table 5) for regions 1, 4, 5 and 7 were limited at each interval by the ± 3% constraints.

Table 5. *Periodic change in volume within each region for the ± 3% fluctuation model.*

Period	*Region*						
	1	*2*	*3*	*4*	*5*	*6*	*7*
				%			
1998-1999	3.0	3.0	3.0	3.0	3.0	3.0	3.0
1999-2000	3.0	3.0	1.3	3.0	3.0	3.0	3.0
2000-2001	3.0	0.8	-3.0	3.0	3.0	-0.6	3.0
2001-2002	3.0	3.0	-1.5	3.0	3.0	3.0	3.0

The ± 2% and ± 1% fluctuation model

As in study 2, the system was unable to produce a valid solution when the level of constraints (i.e. regional, periodic and national HSS/Coillte fluctuations) was set at ± 2% and ± 1%. The reason was that the constraints, especially Coillte's production targets constraints, were too restrictive and the HSS could not find a feasible solution. This is an indication that Coillte's current production smoothing process may result in unrealistic and infeasible harvest volume estimates (Nugent 1998).

Summary of the results of study 3

A summary of the results obtained in this study highlights the percentage decrease in the total NPV and the NPV/m³ by comparison with the 'no constraints' study (Table 6). For example, a total NPV of £303.1 million was obtained from the ± 10% fluctuation model. The cost of applying these constraints represents a decrease of 10.1% from the NPV obtained in the 'no constraints' study. The volume harvested decreased from 15.5 million m³ to 15.2 million m³ and the NPV/m³ was reduced to £19.98. This reduction represents a decrease of 8.0% in the NPV/m³ from the 'no constraints' study.

Table 6. *Summary of the results from study 3 ('periodic fluctuating volume constraints').*

Model	*NPV*	*Decrease in NPV from the 'no constraints' study*	*Total volume*	*NPV*	*Decrease in NPV/m³ from the 'no constraints' study*
	Million £	*%*	*Million m³*	*£/m³*	*%*
The 'no constraints' study	337.0	-	15.5	21.72	-
The ± 10% fluctuation model	303.1	10.1	15.2	19.98	8.0
The ± 5% fluctuation model	294.0	12.7	15.0	19.58	9.8
The ± 3% fluctuation model	289.1	14.2	14.9	19.43	10.5
The ± 2% fluctuation model	–	–	–	–	–
The ± 1% fluctuation model	–	–	–	–	–

Periodic increasing volume production models (study 4)

In the second study, two scenarios were analysed which included volume constraints to ensure a non-declining wood supply, with annual regional volume production increases of at least 1% or 5%, depending on the constraint files used. As outlined previously, national (total) volume constraints were included, whereby the maximum fluctuations of the HSS volumes from Coillte's harvest forecast volumes were set at ± 1% and ± 5% of the forecast volumes.

The + 1% production model

As stated, the periodic volume harvested was set to increase by a minimum of 1% each year within each region. The output from this non-declining wood supply resulted in an NPV of £286.7 million (Table 7). Thus a cost penalty was incurred which represented a decrease of 14.9% from the NPV obtained in the 'no constraints' study (see Table 8 for a summary of the results). The results also showed that the volume harvested decreased from 15.5 million m^3 to 14.8 million m^3 and the NPV/m^3 reduced to £19.33. This change represents a decrease of 11.0 % in the NPV/m^3 from the 'no constraints' study.

Further analysis of the regional production values showed that each region, with the exception of region 4, produced volume increases of exactly 1% at each given interval. In the case of region 4, an increase of 50.9% in the volume harvested between 1998 and 1999 was forecast. Similarly, an increase of 12.2% was forecast between 2001 and 2002.

Table 7. *Regional production volumes with a minimum increase of 1% each year.*

				Region				
Year	*1*	*2*	*3*	*4*	*5*	*6*	*7*	*Total*
				m^3				
1998	383,802	418,137	505,890	321,178	345,423	454,709	339,363	2,768,502
1999	387,640	422,320	510,950	484,638	348,875	459,257	342,749	2,956,429
2000	391,517	426,541	516,064	489,492	352,363	463,847	346,180	2,986,004
2001	395,430	430,814	521,222	494,387	355,887	468,496	349,648	3,015,884
2002	399,386	435,118	526,435	554,875	359,447	473,170	353,138	3,101,569
Total	1,957,775	2,132,930	2,580,561	2,344,570	1,761,995	2,319,479	1,731,078	14,828,388

The + 5% production model

A further scenario in this case study was examined whereby the regional volumes harvested in each period over the time span 1998-2002 were set to increase by a minimum of 5%. Similar results to those obtained in the previous scenario were achieved. The total NPV obtained was further reduced, as was the NPV/m^3 (Table 8). This was a direct result of applying more restrictive constraints. The volume harvested also decreased from 14.8 million m^3 to 14.7 million m^3 by comparison with the + 1% model. Furthermore, it became evident that each region produced exactly the minimum volume increases (5%) that were set out in the regional volume constraints.

Summary of the results of study 4

A summary of the results obtained in this study (Table 8) showed that an NPV of £286.7 million was obtained from the + 1% production model and that the cost of applying these constraints represented a decrease of 14.9% from the NPV obtained in the 'no constraints' study. The volume harvested also decreased from 15.5 million m^3 to 14.8 million m^3 and the NPV/m^3 was reduced to £19.33. This represents a decrease of 11.0% in the NPV/m^3 obtained in the 'no constraints' study. In the + 5% production model the NPV and the NPV/m^3 were further reduced to £283.3 million and £19.26 respectively, however the additional reductions were small in comparison to the ones associated with the +1% production model.

Table 8. *Summary of the results from study 4 ('periodic increasing volume production').*

Model	*NPV*	*Decrease in NPV from the 'no constraints' study*	*Total volume*	*NPV*	*Decrease in NPV/m³ from the 'no constraints' study*
	Million £	*%*	*Million m³*	*£/m³*	*%*
The 'no constraints' study	337.0	–	15.5	21.72	-
The + 1% production model	286.7	14.9	14.8	19.33	11.0
The + 5% production model	283.3	15.9	14.7	19.26	11.3

Even though species constraints were not included in these + 1% and + 5% increasing volume production models, a comparison of the volumes of Sitka spruce produced with those in the 'no constraints' study showed that a smoothed species wood supply was achieved as an indirect result of the total volume regulation constraints (Figure 2). For example, the difference between the 1999 and 2000 volumes in the 'no constraints' study was –406,000 m^3. This was reduced to –60,000m^3 in the + 1% production model and to +8,000 m^3 in the + 5% model.

Discussion

Periodic fluctuating volume constraints (study 3)

The purpose of this study was to evaluate the capability of the HSS to produce a harvest schedule consisting of regulated volume supplies for each period within each region and to determine the associated decrease in net present revenue as compared with the 'no constraints' study. A summary of the results obtained in the study is presented in Table 6. A similar pattern of 'exponential' decrease in NPV was achieved in this study (Figure 3) as reported previously for study 2 (Nieuwenhuis and Nugent 2000). The reason was, that as constraints became more restrictive, the number of management options to choose from rapidly decreased and more and more financially unattractive options had to be included in the solution in order to continue to satisfy the model specifications.

This study resulted in a number of conclusions. First, regional targets that reduce annual fluctuations in the level of production but are still compliant with the company forecast can be produced by the HSS. The results show that the demand of management for regulated periodic regional production volumes has a significant negative impact on overall profits. Hence, careful evaluation of regional volume regulation requirements is essential.

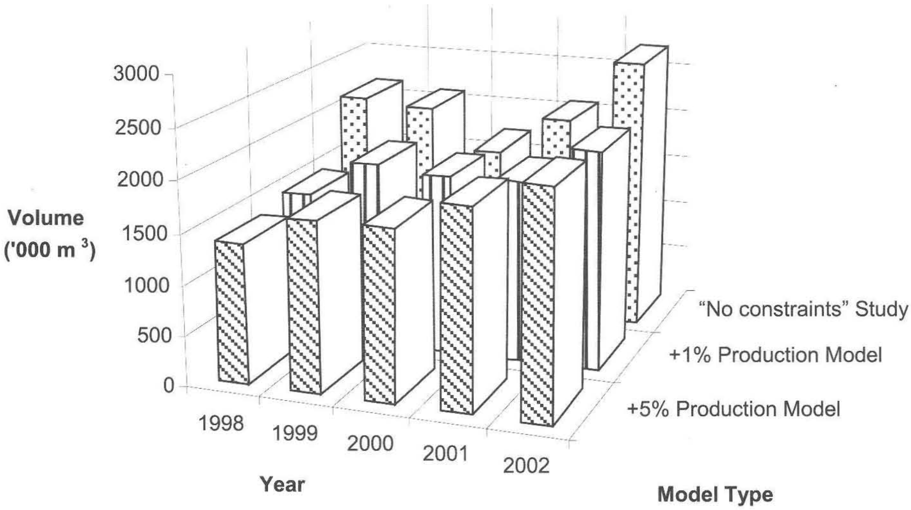

Figure 2. *Comparison of the production volumes for Sitka spruce by period for different models.*

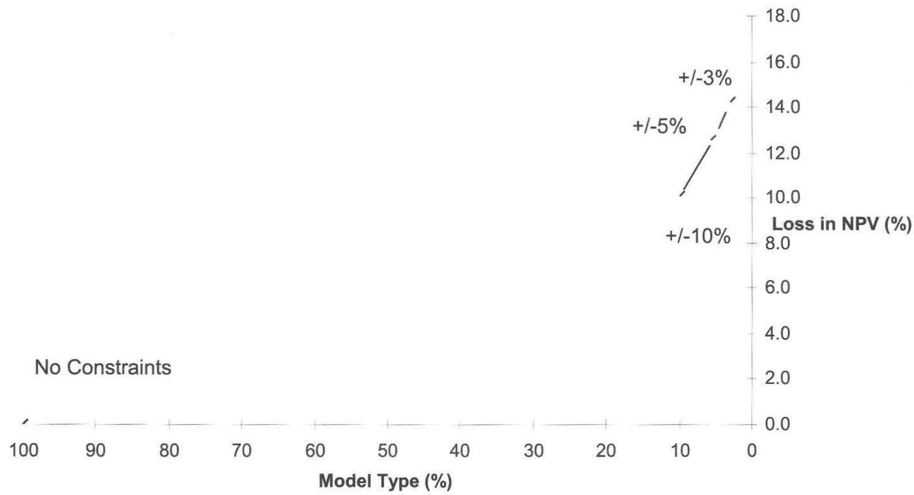

Figure 3. *Percentage reduction in NPV where production fluctuation constraints have been applied.*

Finally, the costs of various levels of smoothing were determined. For example, a comparison between the 'no constraints' study and the ± 3% fluctuation model shows a loss of £47.92 million in NPV over the five year period (Table 6).

Periodic increasing volume production models (study 4)

The aim of this case study was to examine the suitability of the HSS to produce a harvest schedule consisting of an increasing supply of wood year on year for each region and to ascertain the impact on NPV of implementing such a harvest schedule. An increasing supply of wood is desirable so as to cope with anticipated growth in demand from the processing sector. This aim was achieved using two constraint sets: the volume produced within each region was set to increase by a minimum of 1% or 5% per year (Table 8). However, a considerable cost penalty was incurred in this study (Figure 4).

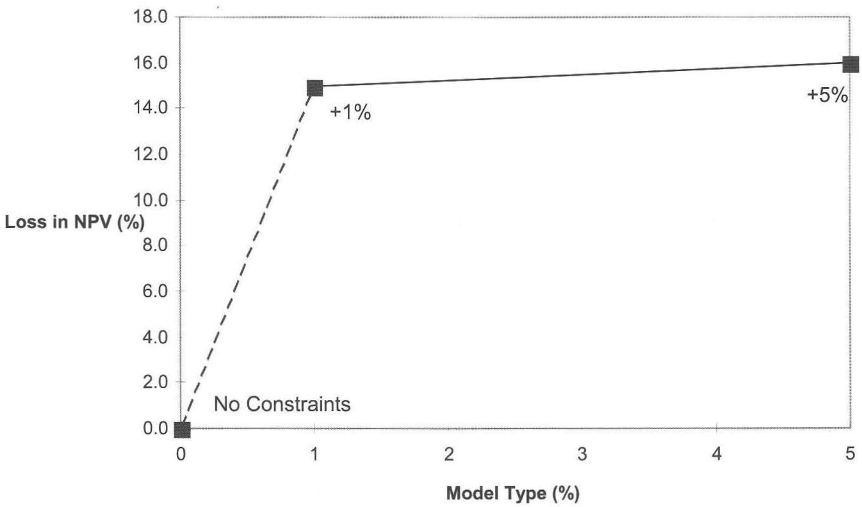

Figure 4. *Percentage decrease in NPV where periodic increasing volume constraints were applied.*

Analysis showed that it was possible to produce a periodic increasing supply of wood from each region. However, while the periodic increase in regional harvest volumes may be feasible (due to the general age-class structure of Irish forests), it is clearly inadvisable for economic reasons to implement it rigidly. Results presented in this study indicate that the cost, in terms of reduced NPV, is high, irrespective of the level of annual increase imposed. The reason for imposing this type of constraint on the production levels has to be carefully evaluated in order to be able to weigh the costs and benefits to Coillte. The relevance in relation to the requirements of the processing industry should also be examined.

It is interesting to note that each region produced volume increases of exactly + 1% or + 5% for both scenarios (the models with annual volume production increases of at least 1% and 5%) with the exception of region 4 in the + 1% production model. In this case an increase of 50.9% (Table 8) in the volume harvested between 1998-1999 was produced. Similarly, an increase of 12.2 % was achieved between 2001-2002. A possible explanation is that the forest age class structure in region 4 is the most flexible in relation to harvest scheduling, and is used to 'allow' the other regions to achieve the required periodic volume increases.

Sustainability

The current model is designed for short-term operational planning. However, the basic model structure is also very suitable for more long-term strategic planning, for analysis of long-term supply commitments and for investigations of sustainable wood harvest management practices.

Presently, the model does not use ending constraints that would ensure that the level of harvesting would not exceed the increment of the Coillte forest estate. This control is currently achieved by the definition of allowable management options and by specifying constraints that either control the level of production for the entire planning period or for each year within the planning period. The result of introducing ending constraints would be a model that could be used to determine the appropriate level of production compatible with long-term sustained yield. However, this would require significant model modification and was outside the scope of the investigations reported here.

Another method of investigating the sustainability of the wood harvest would be to use the five-year model in a stepwise fashion. This would necessitate running the model from 1999 to 2003, then from 2000 to 2004 and so on, and to use the results from each run as production constraints in the following run. The forecast in its present form allows for a maximum planning horizon of 20 years. To allow for long-term planning, the forecast would require a certain amount of development work (i.e. felled stands would have to be reintroduced as young regenerated stands).

Conclusions

The HSS prototype is a complex decision-support tool. As a result a degree of specialisation is required to operate the system. It is not designed to replace forest management decision making but should be used as a planning tool to assist in the efficient scheduling of Coillte's harvest programme. The main benefits are the integration of spatial and temporal harvest scheduling, the production of optimal feasible harvest schedules, and the efficiency with which these are produced. This study has illustrated that the HSS can provide decision-support for Coillte managers at nation-wide and regional levels.

The HSS was successfully used to design forest management strategies that satisfied a range of detailed management and processing industry demand requirements. The resulting detailed national and regional harvest schedules, combined with the associated NPV and NPV/m^3 values, provides forest managers with the type of information necessary to make decisions that balance conflicting demands on the forest estate. As a result, the use of the HSS has the potential to generate significant savings in terms of time and money. The precise quantification of the monetary savings obtainable through the implementation of the HSS with Coillte's harvest scheduling procedures is difficult, but indicators from the analyses carried out in this study are that potential savings of several million pounds over a five year period can be expected. In a study carried out by Williamson (1991), Coillte's wood production scheduling, allocation and haulage routes were compared with the optimal solution as suggested by the HSS, and a possible saving of up to £1.0 million per year was indicated. The savings in terms of time are impossible to estimate, as these are dependent on the level of integration of the HSS with current planning procedures.

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