A Multi-Objective Programming Model for Forest Management Planning Problem to Sustain Water Allocation

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Abstract. Forest management planning is placed not only on managing timber production but also on maintaining forest ecosystem values, such as water preservation. Thus, the meaning of sustainable forest management has broadened from sustainable timber management to ecosystem-based multipurpose forest management. This paper discusses the need to preserve water by forest in such a way the water will flow to rivers to be used as a resource to generate hydroelectric power plant. The problem is then modeled as a multi-objective integer programs.

1. Introducing

Today, there is a frightening loss of forest ecosystems in all tropical regions (particularly Indonesia) due to changes in land use. Furthermore, extensive forest and forest forest areas in most regions are degraded to varying degrees by damage caused by pests, disease, fire and atmospheric pollution, climate change and lack of management or unsustainable forest management [1].

A good forest management which is integrated to ecological system would give positive impact to maintain the availability of water, in such a way the deposit water will run flow to the surrounding rivers. Rivers which have certain water debit can be utilized to generate electricity, which is called renewable energy to produce electricity. This kind of electric generator is called Water Energy Electric Generator.

Sustainable management is generally defined as the process of reaching and maintaining objectives for the purposeful use and spending of money, human resources, material resources and knowledge [2]. In particular, forest management applies resources to the forest ecosystem in order to achieve sustainability objectives. An objective is an appealing condition for which someone is willing to allocate resources (time effects money, etc.). Since management is intended to achieve objectives, they must be defined before appropriate management measures can be determined. The objectives act as a major organizational framework for analysis, management recommendations and performance assessment. It is impossible to determine what to do without objectives and to evaluate how well it has been done [3].

Optimization models were developed to address key issues in the area and to increase clustering and compactness in the selection of reserve sites. In order to minimize the cost of acquiring critical core habitats for reserve selection, [4] has developed a mixed integer programming (MIP) model. The landscape has been divided into parcels of squares. Each parcel uses a binary decision variable to track whether it is chosen as a critical core parcel. Relations between buffer parcels and core parcels are recognized. Instead of directly modeling the core areas. In order to promote the clustering of selected
reserve sites, [5] used a different type of MIP model to minimize the external perimeters of preserved areas. In either approach, however, landscape dynamics related to forest growth and management activities, such as harvesting, are not taken into account.

In this paper we emphasize a sustainable forest management in which one of the goal is to conserve water retention in the forest in order to act as water resource for rivers surroundings. The rivers can be used to operate a hydroelectric power station.

2. Methodology
The optimization model for sustainable forest management planning will also include other economic and forestry criteria, such as net present value, volume control, area control and rest inventory. All criteria can be efficiently integrated into a mathematical programming model using goal programming techniques.

Nomenclature
Parameters
X total forest area
K number of forest sections (1, . . . , k, . . . , K)
Z number of site classes (1, . . . , z, . . . , Z)
I number of initial age classes (1, . . . , i, . . . , I)
J number of prescriptions, defining a complete treatment schedule for the whole planning horizon (1, . . . , j, . . . , J) (these prescriptions are defined following the model I structure (Johnson and Scheurman, 1977))
T planning horizon
t time unit
L = T/t number of cutting periods (1, . . . , l, . . . , L)
t’ time span that defines the final age class
S = T/t’ number of final age classes (1, . . . , s, . . . , S)
Bb total forest area divided by the planning horizon T and multiplied by the time span t’ that defines the age class
X_{zi} area corresponding to zth site class and ith initial age class
NPV_{zij} net present value per hectare harvested from zth site class, ith initial age class at jth prescription
NPV* target for the net present value
V_{zil} volume per hectare from zth site class, ith initial age class at lth cutting period
V_{zi}^i volume of initial forest inventory on kth section
\gamma proportion of carbon contained in timber biomass
r vector of normaliser factors for the criteria considered
w vector of preferential weights for the criteria considered
CB* target for total carbon balance

Index sets
Q_j index set of prescriptions that involve no harvests
Q_k index set of prescriptions belonging to the kth section

Variables
X_{zij} hectares harvested from zth site class, ith initial age class at jth prescription
NPV_{zij} net present value per hectare harvested from zth site class, ith initial age class at jth prescription
H_l volume harvested at lth cutting period
X_s area belonging to sth final age class at the ending period
V_{zij}^f volume of ending forest inventory of zth site class, ith age class at jth prescription
The International Conference on Computer Science and Applied Mathematics
IOP Conf. Series: Journal of Physics: Conf. Series 1255 (2019) 012062
doi:10.1088/1742-6596/1255/1/012062

\[ X_{zij}^f \] hectares uncut from zth site class, ith age class and jth prescription at the ending period

\[ V_k^f \] volume of ending forest inventory on kth section

\[ V^l \] volume of forest inventory at the end of lth cutting period

\[ X_{zij}l \] hectares harvested from zth site class, ith initial age class, jth prescription at lth cutting period

\[ CB_l \] carbon balance at lth cutting period

\[ CE_l \] carbon emission at lth cutting period

Deviation variables

- \( n_{NPV}, p_{NPV} \): negative and positive deviation variable for the net present value criterion
- \( n_{H_l}, p_{H_l} \): negative and positive deviation variables for the volume control goal \( (l = 1; \ldots; L - 1) \)
- \( n_{f}, p_{f} \): negative and positive deviation variables for the area control goal \( (\forall s) \)
- \( n_{lH}, p_{lH} \): negative and positive deviation variables for the ending forest inventory goal \( (\forall k) \)
- \( n_{CB}, p_{CB} \): negative and positive deviation variable for the total carbon balance goal

3. Results and Discussion

As the suitable model for this problem belongs to multi criteria decision analysis, it is then necessary to set up criteria. The following criteria can be considered.

a. to maximize the net present value of the forest;

b. to equalize harvest volume in each cutting period;

c. to equalize the forest area control criterion;

d. to ensure that the ending forest inventory is larger than or equal to the initial inventory;

e. to maximize the total carbon balance over the planning horizon.

Constraints

\[ \sum_{j=1}^{J} X_{zij} = X_{zi} \quad \forall z,i \] (1)

Constraints (1) is for area accounting to acquire that the sum of the hectares connected to each prescription has to be equal to the area conforming to each site class and to each age class.

Goals

Firstly is for net present value

\[ \sum_{z=1}^{Z} \sum_{i=1}^{I} \sum_{j=1}^{J} NPV_{zij} X_{zij} + n_{NPV} - p_{NPV} = NPV^* \] (2)

Depending on the area accounting constraints (1), the objective (2) can be achieved by maximizing the net present value.

Therefore, NPV is a baseline value and the underperformance variable \( n_{NPV} \) is unwanted and its minimisation implies the maximization of the net present value.

Second goal is for volume control

\[ \sum_{z=1}^{Z} \sum_{i=1}^{I} \sum_{j=1}^{J} V_{zij} X_{zij} = H_l \quad \forall l \] (3)

\[ H_{l+1} - H_l + n_{lH} - p_{lH} = 0, \quad l = 1, \ldots, T - 1 \] (4)

Equations (3) and (4) are to impose a restriction of flow of timber volume harvested in each of the T cutting periods. Therefore, the under achievement nlH and the over-achievement plH of goal 4 are not necessary and consequently they would have to be minimised.
Third goal is for Area control

\[ X_s + n_s f - p_s f + b \quad \forall s \]  
\[ X_s = \sum_{s=1}^{Z} \sum_{j=1}^{f} \sum_{l=1}^{j} X_{zil} \quad \text{if} \quad s = 1 \]  
\[ X_s = \sum_{s=2}^{Z} \sum_{j=1}^{f} X_{zil} \quad \text{if} \quad 1 < s \leq S \]  

Eqs. (6) and (7) define the number of hectares in each of the final S - age classes. If a perfectly regulated forest is desired, areas \( X_s \) should be equal to B for each final age class. Therefore, the negative \( n_f \) and positive \( p_f \) variables that define the goal (5) are unwanted and should be minimized. 

The fourth goal is for forest inventories.

\[ \sum_{z=1}^{Z} \sum_{j=1}^{f} \sum_{l=Q_s}^{j} V_{z}^l X_{zil} = V_{zil}^l \quad \forall k \]  
\[ V_{zil}^l + n_{k} I - p_{k} I = V_{zil}^l \quad \forall k \]  

The equations (8) and (9) of the final forest inventories establish a relation between the initial and final forest inventories. If the figures in the initial inventory are considered appropriate to ensure the continuation of the forest harvest, the negative \( n_I \) and positive \( p_I \) variables of objective (9) are not desired and should be minimized. On the contrary, if the initial inventory figures are considered inadequate, only the negative \( n_I \) deviation variable should be minimized. 

The fifth goal is for carbon balance

\[ CBl = [\gamma (V^l - V^{l-1} + H_i) - CE_l] \quad \forall l \]  
\[ V^1 = \sum_{z=1}^{Z} \sum_{j=1}^{f} X_{zil} - \sum_{j=1}^{f} X_{zil} V_{zil} \]  
\[ V^2 = \sum_{z=1}^{Z} \sum_{j=1}^{f} X_{zil} - \sum_{j=1}^{f} \sum_{l=1}^{j} X_{zil} V_{zil} + \sum_{z=1}^{Z} \sum_{j=1}^{f} \sum_{l=1}^{j} X_{z(e1)} \sum_{j=1}^{f} X_{zil} \]  
\[ \ldots \]  
\[ \sum_{l=1}^{L} CB_l + nCB - pCB = CB^* \]  

Eq. (10) evaluates the net carbon balance in the generic cutting period \( l \)th. This balance is phrased as the difference between timber biomass growth plus the harvest minus CE for carbon emissions per period. In the next section, an explanation of how to estimate carbon emissions will be provided in accordance with the methodology proposed by Row and Phelps (1996). Eqs. (11) and (12) present a dynamic evolution of the forest inventory structure in each period, \( V_{z(e1)} \) being the volume per hectare of \( z \)th site class derived from the first period of harvest. Finally, the aim for the total carbon balance of \( CB^* \) is achieved by maximizing \( \Sigma_{l=1}^{L} CB_l \) in line with the accounting constraints set out in Eq. (1). Therefore, \( CB^* \) is an anchor value and thus minimizing the negative deviation variable \( nCB \) means maximizing the total carbon acquired along the planning horizon \( T \). 

The sixth goal for water protect

\[ \Sigma x_{z} [(f_k - f_r) - Q] = Q \]  

Eq. (14) ensures that target flow rate \( Qt \) for river to operate HPS can be fulfilled. 

Water \( f_k \) is given as

\[ f_k = \frac{1}{2} S_i t^{\frac{1}{2}} + \frac{1}{2} (k_i + k_o) \]  

Water exfiltration, \( f_r \) is given by

\[ f_r = \frac{1}{2} S_i t^{\frac{1}{2}} - \frac{1}{2} (k_i + k_o) - M E \]
and surface run off Q is written as $Q = 0.0028 \text{CiX}$

### 4. Conclusion

The sustainable forest management model involves water preservation as well as the other criteria such as net present value, volume control, area control, and carbon balance. Goal programming technique is suitable for the management model.

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