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Mathematical Optimisation Model for Management of Sago Palm Plantation Expansions

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Sago palm is an important indigenous crop grown in Southeast Asia. Its main product, sago starch, has the potential to be an alternative source of starch when compared to traditional starch derived from maize, sweet potato, cassava etc. Despite its potential, sago has remained as wild forest trees in swampy areas and unutilised for decades. Recently, Malaysia and Indonesia have shown interest in establishing estate plantations of sago palms. Although such a development may be welcomed, it is advisable to exercise caution during expansion of sago plantations. It is highly likely that unplanned expansions may result in large scale clearing of the tropical and peatland forests that are densely concentrated. In this respect, the vulnerability of these sensitive ecosystems during sago plantation expansions must be carefully accounted for. Therefore, in order to ensure planned and minimal sago plantation expansion, decision support tools that help to strategies land use changes (LUC) is crucial. Thus, this work presents a mathematical optimisation model of the type mixed integer linear programming (MILP) to plan for sago plantation expansions. The proposed model determines whether land expansion would be required when demands increase, accounting for the cost involved in expansion. A simple sago value chain has been solved to illustrate the proposed model. The results show that the optimised results avoided 4.3 % - 9.3 % of possible land area under expansion; 2.96 – 4.05 times of CO₂ emission and 120.16 % - 189.14 % of cost savings.

1. Introduction

Sago starch is a potential and emerging alternative to traditional starch varieties. Sago starch is produced from sago palms. The commercial cultivation of sago palm has led to the development of sago plantations. The demand for sago starch is expected to increase due to favourable government policies and market dynamics, especially in the south Asian and Asia Pacific region (Mohamad et al., 2016). Considering these developments, there may arise a need in the future for expanding the sago plantations to cater to this increased demand. Under this circumstance, it becomes very important to strategies the expansions to have minimal environmental impact from LUC (Sheikhi et al., 2018). It can be noted that few previous works have attempted to optimise the land use. Accorsi et al. (2015) developed a model to solve land allocation problem in agro value chains. Li et al. (2019) proposed a model for agricultural energy-water-food (EWF) nexus management, in which, optimisation of land allocation for agriculture is also addressed. Hao et al. (2017) developed an optimisation model for spatial spread of different crops within a region to effectively utilise the land and water resources. It can be noted that most of the works were involved in optimising the allocation of existing land resources for different land uses (Wosten and Ritzema, 2001); but very limited works have attempted to optimise the expansion of new lands (only if required) into the agro value chain. The current work aims to address this research gap by developing a model that aids decision maker to plan sago plantation expansions based on the forecasted demand for sago starch. The optimisation of expansion is achieved by minimising the expansion cost and carbon penalty cost. The carbon penalty cost is levied due to emissions

from LUCs. Th cost minimisation indirectly promotes minimum usage of new lands for expansion and avoidance of excessive land disturbance and associated biodiversity loss due to unplanned expansion. In fact, Van Fan et al. (2019) emphasised on the need for more efficient management of virgin resources in order to reduce pollution. Moreover, the current approach contains novel binary formulations that are analogous to decision-making approaches in utility systems (Velasco-Garcia et al., 2011), making the model simpler and more efficient when compared to other previous works. Furthermore, the approach uses cost for minimising expansions, making it more relevant in decision making especially in developing countries. The next section defines problem and the superstructure of sago value chain. Next, Section 3 explains the mathematical model formulation for this work. Following this, an illustrative case study is presented in Section 4. Lastly, Section 5 draws on the conclusions and future work.

2. Sago plantation expansion

The problem statement that the current work aims to address is discussed in this section. Figure 1 illustrates a general representation of a sago value chain. As shown in Figure 1, a set of existing sago plantations and potential lands for sago plantation development $p \in P$ with area A_p and plantation density $Z_{p,t}$ is considered in the value chain. The potential lands for sago plantations p are selected such that they are within the 100 km radius of the sago mill s . The sago plantations yield sago logs as the primary product of harvest and is transported to the sago mills. At the sago mills $s \in S$, the sago logs are processed to produce sago starch as the final product. As discussed, the expected increase in sago starch demand may lead to unplanned excessive deforestation for expansion of sago plantations. Therefore, to ensure minimal sago palm plantation expansions, a simple model is proposed.

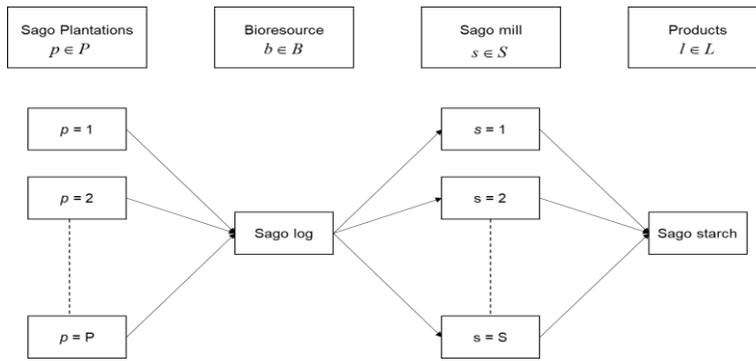


Figure 1: Generic superstructure of sago value chain

The proposed model is developed based on the general superstructure presented in Figure 1. Superstructure optimisation has been used in many other works such as life cycle optimisation (Wan et al., 2014) and biorefinery design (Ng et al., 2015). The next section further describes the general mathematical model formulation.

3. Mathematical model formulation

This section presents the mathematical formulation in developing the model to represent the sago value chain shown in Figure 1. It also presents the equations used for estimating the expansion cost and the carbon penalty cost. The following sub sections discuss the equations in detail.

3.1 Material flow balance

The sago plantation and the potential lands for plantation $p \in P$ with area A_p (ha) has plantation density of $Z_{p,t}$ (palms/ha) in the time period t . The plantations $p \in P$ have sago palms with varying maturity at any time period t . The sago palms are harvested when they reach maturity, usually 9 y to 12 y. The amount of sago palms harvested in the period t , $K_{p,t}$ should be less than the total available sago palms, $Z_{p,t}$ and is shown in Eq(1),

$$Z_{p,t} \geq K_{p,t} \quad \forall p \forall t \quad (1)$$

where, $K_{p,t}$ (palms/ha/y) is the number of palms harvested from the total available palms in plantation. When, $V_{p,t}^{log}$ (t/palm/y) is the yield of sago logs - and $GF_{p,t}$ is the growth factor of the plantation $p \in P$ during the period

t , then the total amount of sago logs harvested from the plantation p in the period t , $X_{p,t}^{PL_log}$ can be determined as shown in Eq(2).

$$X_{p,t}^{PL_log} = K_{p,t} A_p V_{p,t}^{log} G F_{p,t} Y_{p,t}^{new} \quad \forall p \forall t \quad (2)$$

where, $Y_{p,t}^{new}$ is the binary variable activated for those plantations that are part of the value chain. It is explained in detail at section 3.3. The growth factor, $G F_{p,t}$ is a parameter keyed in by the decision maker based on the soil, climate and hydrology factors over the entire sago palm growth cycle. The parameter values vary between 0 to any number. For example, if the value is 1.5, then the growth is 50% better than the baseline period. The total quantity of sago log yield from all the plantations $p \in P$ in the period t , X_t^{Log} (t/y) can be determined as shown in Eq(3)

$$X_t^{Log} = \sum_{p=1}^P X_{p,t}^{PL_log} \quad \forall t \quad (3)$$

The harvested sago logs collected from all plantations $p \in P$ are then transported to the sago mills $s \in S$ as shown by Eq(4).

$$X_t^{Log} = \sum_{p=1}^P \sum_{s=1}^S X_{p,s,t}^{SMill} \quad \forall t \quad (4)$$

where, $X_{p,s,t}^{SMill}$ (t/y) is the quantity of sago logs transported from plantation p to sago mill s with total capacity, Z_s^{SMill} (t/y) during the period t and is presented in Eq(5).

$$Z_s^{SMill} \leq \sum_{p=1}^P X_{p,s,t}^{SMill} \quad \forall s \forall t \quad (5)$$

In the sago mills $s \in S$, the sago logs are processed to produce sago starch. The quantity of sago starch produced from all the sago mills during the period t , X_t^{starch} (t/y) can be determined as shown in Eq(6).

$$X_t^{starch} = \sum_{p=1}^P \sum_{s=1}^S F_{p,s,t}^{SMill} V_s^{starch} \quad \forall t \quad (6)$$

where, V_s^{starch} is the conversion factor for the sago logs at the sago mill s to sago starch. The model optimises the sago plantation expansion depending on the expected increase in sago starch demand. This demand is given as a constraint as shown in Eq(7)

$$X_t^{starch} = D_t^{starch} \quad \forall t \quad (7)$$

where, D_t^{starch} is the expected increased demand for sago starch at time period t .

3.2 Expansion optimisation

The model optimises the land for expansion based on the binary formulation which was previously used by Rajakal et al. (2019). The binary equations provide a simpler approach to optimise land selection compared to other previous works related to land allocation. The following equations, Eq(8), Eq(9) and Eq(10) present the binary formulation,

$$Y_{p,t-1}^{current} \times Y_{p,t}^{change} = 0 \quad \forall p \forall t \quad (8)$$

$$Y_{p,t}^{change} - Y_{p,t}^{new} \leq 0 \quad \forall p \forall t \quad (9)$$

$$Y_{p,t}^{change} + Y_{p,t-1}^{current} - Y_{p,t}^{new} \geq 0 \quad \forall p \forall t \quad (10)$$

The parameter, $Y_{p,t-1}^{current}$ indicates if the plantation p is existing at the period previous to t . Value "1" is keyed in to the existing plantations and value "0" to the potential plantations by the decision maker at the start of the optimisation. The binary variable, $Y_{p,t}^{new}$ indicates the status of the plantations and the potential lands after optimising the expansion to meet the demand expected for the period t . Here, value "1" is given to all the plantations in the value chain but "0" to the potential new lands at the period t . $Y_{p,t}^{change}$ is also a binary variable which is assigned value "1" only for those plantation p that are newly added to the value chain in the period t .

$Y_{p,t}^{change}$ helps to ascertain the expansion cost and optimise the lands for expansion. Table 1 shows the working of the binary formulation and the logic for assigning the values for $Y_{p,t}^{change}$. The working of the above equation is explained more briefly by Rajakal et al. (2019).

Table 1: Likely outcomes for the binaries $Y_{p,t-1}^{current}$, $Y_{p,t}^{new}$ and $Y_{p,t}^{change}$

$Y_{p,t-1}^{current}$	$Y_{p,t}^{new}$	$Y_{p,t}^{change}$
0	0	0
0	1	1
1	0	0
1	1	0

3.3 Carbon footprint estimation

LUCs typically involves either emission or sequestration of CO₂ and it depends upon the nature of LUC. For example, LUCs of tropical or peat lands to sago plantations results in emission whereas conversion of grasslands or barren lands results in sequestration. The carbon footprint from the LUCs for sago plantation expansion can be estimated as shown in Eq(11). Carbon footprint accounting is widely seen as a metric for environmental and climate change impacts (Jamaludin et al., 2019)

$$Carbon_t^{Emission} = \sum_{p=1}^P A_p C_{p,t}^{LUC} Y_{p,t}^{change} \quad \forall t \quad (11)$$

where $C_{p,t}^{LUC}$ (tCO₂-eq /ha/y) is the annualised CO₂ emission from per hectare of potential land p due to LUC to sago plantation. The carbon emissions are accounted into the expansion cost in the form of carbon penalty cost. This is achieved by multiplying a cost penalty factor, $C^{Penalty}$ (USD/ tCO₂-eq) to the total emissions from plantation p and then accounting it while estimating the expansion cost. The carbon penalty cost due to carbon footprint, $Cost_t^{Penalty}$ (USD) associated with planation p due to LUC emissions can determined as shown in Eq(12),

$$Cost_t^{Penalty} = \sum_{p=1}^P A_p C_{p,t}^{LUC} Y_{p,t}^{change} C^{Penalty} T^{Period} \quad \forall t \quad (12)$$

where, T^{Period} is the number of years considered for estimating the carbon footprint from the period t in which the expansions is initiated.

3.4 Expansion cost

As discussed previously the expansion costs considered in the current work are deforestation, planting and carbon penalty costs due to carbon emissions. These costs are one-time upfront investment in developing a new sago plantation and do not recur periodically. The expansion cost, $Cost_t^{Expansion}$ (USD) can be determined as shown in Eq(13).

$$Cost_t^{Expansion} = \sum_{p=1}^P [Cost_p^{Deforestation} + Cost_p^{Planting}] \times A_p \times Y_{p,t}^{change} \quad \forall t \quad (13)$$

where, $Cost_p^{Deforestation}$ (USD/ha) is the cost of land clearing of potential land p for sago plantation, $Cost_p^{Planting}$ (USD/ha) is the cost of planting of sago palms at the potential land p and $Y_{p,t}^{change}$ is the binary variable used for land selection. The deforestation and planting costs are taken from the works of Abdul Samad et al. (2009) and Latif et al. (2003).

3.5 Objective function

The sago plantation expansion is optimised by minimising the expansion cost and carbon penalty cost as presented in Eq(14). A plantation expansion always results in cost which is typically a one-time initial investment on the land resource. The expansion costs and the carbon penalty cost are influenced by the area of the lands for expansion and not by other factors like market dynamics, yield, etc. Therefore, minimising the expansion cost indirectly results in minimising the land expansions. When the expansions are minimum there is obviously less stress on natural resources and the environment.

$$Minimise (Cost_t^{Expansion} + Cost_t^{Penalty}) \quad \forall t \quad (14)$$

4. Illustrative case study

A case study of a sago mill company in Malaysia is presented in this section to illustrate the developed approach shown in Section 3. Figure 2 shows the superstructure of the considered sago mill company. The

sago mill has annual maximum production capacity (Z_s^{SMill}) of 8,250 t of sago starch. The existing sago plantations supply 21,825 t of sago logs annually to the sago mill. The annual production of sago starch is 4,365 t. PP 1 – 6 are potential new lands identified for sago plantation expansion to meet any increase in demand for sago starch. The identified potential lands are secondary tropical forests and swampy peat lands. The area is defined as fixed input values and is presented in Table 2. The deforestation and planting costs of secondary tropical forest and peat lands are also presented in Table 2. The conversion factor of harvested sago palms to sago logs at the plantations, $V_{g,t}^{log}$ (t/palm/y) is taken as 0.50 and the conversion factor of sago logs to sago starch at the sago mill, V_f^{starch} is taken as 0.20 (Wan et al., 2015). The number of palms harvested from the plantations, $H_{g,t}$ (palms/ha/y) is taken as 100. The growth factor, GF_t of the sago plantations are presented in Table 2. The annual carbon emission $C_{p,t}^{LUC}$ from tropical forests and peat lands are taken as 14.04 tCO₂-eq /ha/y and 69.04 tCO₂-eq /ha/y. This was obtained by annualising the carbon footprint estimated for 50-year timeframe by Fargione et al. (2008). The cost penalty, $C^{Penalty}$ is fixed as USD 10 per tCO₂-eq emission and the time period, T^{Period} is taken as 25 y. A mixed integer linear programming (MILP) model was developed to solve this case study. The model contained 100 continuous variables, 66 fixed parameters and 113 constraints. The model was solved via LINGO version 18.0. A global optimum solution was obtained within negligible time.

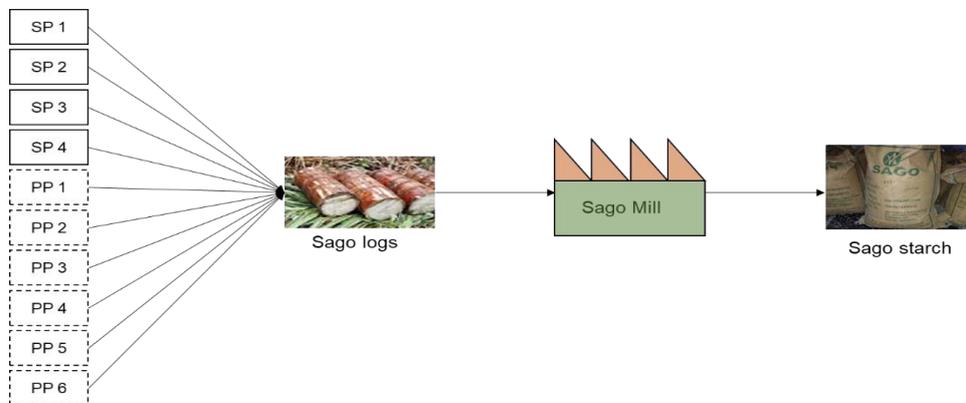


Figure 2: Sago value chain considered in illustrative case study

Table 2: Plantations – Area, Distance to sago mill, Deforestation and Planting cost

Potential new lands	Current land use	Area (ha)	Land clearing cost (USD/ha) ^a	Planting cost (USD/ha) ^b	Growth factor
PP 1	Tropical forest	130	1,010	1,500	1.2
PP 2	Tropical forest	120	1,010	1,500	1.05
PP 3	Peat land	160	885	2,000	1.1
PP 4	Peat land	105	885	2,000	1.2
PP 5	Tropical forest	85	1,010	1,500	1.2
PP 6	Peat land	75	885	2,000	0.9

The expansion analysis is carried out for an increased sago starch demand. It is expected to increase by 6,800 t/y in the next 5 y considering 10 % annual increase in demand ($X_t^{starch}=6,800$ t). As discussed above, the existing sago plantations support sago starch production up to 4,365 t/y from the 21,825 t of harvested sago logs. The potential lands for sago plantation PP 1, PP 2, PP 3, PP 4, PP 5, and PP 6 can yield 7,800 t/y, 6,300 t/y, 8,800 t/y, 6,300 t/y, 5,100 t/y and 3,376 t/y of sago starch. The optimised results have the potential plantations NL 1 and NL 5 selected for expansion. The combination of plantations PP 2 – PP 4 and PP 3 – PP 6 can support sago starch production of 2,520 t/y and 2,435 t/y and are supposed to be appropriate to meet the deficit in production (2,435 t/y). However, the PP 1 – PP 5 combination is selected for expansion due to minimum expansion cost. The total cost (expansion cost and carbon penalty cost) of the combination PP 1 - PP 5, PP 2 - PP 4, and PP 3 - PP 6 is 1.29×10^6 USD; 2.84×10^6 USD and 3.73×10^6 USD. The optimised selection of PP 1 – PP 5 combination compared to PP 2- PP 4 and PP 3 – PP 6 has resulted in possible avoidance of 4.3% and 9.3% of expansion in land area. This includes 105 ha to 235 ha of possible expansions into more sensitive swampy peat lands. This is achieved because the expansion cost involved for peat land is 12.5 % more than the tropical forest. Therefore, by minimising expansion cost and the

carbon penalty cost the model selects the minimum land area that would be needed to meet the demand. The carbon emission from the optimised selection is 3018.6 tCO₂-eq/y whereas the annual emissions from PP 2 – PP 4 and PP 3 – PP 6 combination is 8934 and 12239.8 tCO₂-eq. The optimisation has resulted in avoidance of 5915.4 – 9221.2 tCO₂-eq/y.

5. Conclusion

A MILP model is presented in this work to analyse the minimum expansion required for sago plantations. The novel contribution of this work is minimal land expansion achieved by minimising the costs associated with expansion, which includes deforestation, planting and carbon penalty costs due to emissions from LUC. By considering cost, the model is more practically relevant to developing countries where cost is a major criterion in decision making compared to other environmental indicators. A case study involving a sago mill company is solved to illustrate the model. The current work can be extended to other agro value chains as well. The case study considers only secondary tropical forests and peat lands for expansion though other land types can also be taken for expansion analysis. Furthermore, environmental and social indicators can also be considered for future scope of work.

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