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Life Cycle Optimisation of a Sustainable Sago Value Chain

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In line with global concern on the sustainable development, economic, environmental and social aspects should be considered simultaneously in an entire value chain. In this work, a cradle-to-gate life cycle optimisation (LCO) of sago value chain that involves plantation, harvesting and processing of sago starch as well as transportation of sago starch to customer is developed. In addition, fuzzy optimisation is adapted to minimise both total operating cost and workplace footprint of sago value chain. Note that in this work, the workplace footprint is divided into three levels of risk which are death (D), non-permanent disability (NPD) and permanent disability (PD) risks. These risks and operating cost are considered simultaneously and traded off to identify the optimum pathway with minimum risks as well as operating cost for sago value chain. A realistic case study is solved to illustrate the developed approach.

1. Introduction

Sago palm is a species of genus *Metroxylon*, with scientific name of *Metroxylon sagu*. It grows in tropical lowland forest in South East Asia and Papua New Guinea (Flach, 1997). Sago palm is considered as ‘starch crop of the 21st century’, due to its strong ability to thrive in poor soil conditions (Singhal et al., 2008). During the growing cycle of sago palm, the starch accumulates in the sago trunk in the early growing stages. After approximately ten years of growing, the starch can be extracted from the trunk to produce sago starch. Such starch is one of the carbohydrate sources for humans, and it can be utilised as raw material to produce various food products (e.g., noodles, cakes, biscuits, etc.) or converted into value–added products (e.g., ethanol, sugar, kojic acid, etc.) via various technologies and processes (Singhal et al., 2008). To convert sago palm into sago starch, several steps such as plantation, harvesting and processing of sago starch are involved. The sago starch is then either supplied to local or exported to others countries.

In the previous research works, life cycle assessment (LCA) is used to quantify and evaluate the environmental impact and economic performance (Kniel et al., 1996). LCA was then extended to develop an optimum LCA performance (OLCAP) framework to identify optimum process pathway (Azapagic and Clift, 1999). Later, work environmental footprint was also introduced in LCA by De Benedetto and Klemeš (2009). However, these previous research works were mainly focused on the development of assessment and optimisation methodology, and no research work is conducted on sago value chain. Therefore, in this work, a cradle-to-gate life optimisation (LCO) approach is developed to identify the optimum pathway for sago value chain with minimum total operating costs and workplace footprint. The workplace footprint is divided into three levels of risk which are death (D), non-permanent disability (NPD) and permanent disability (PD) risks. These risks and operation costs are considered simultaneously in each step of sago value chain. Fuzzy optimisation approach is adapted in this work to solve the multiobjective optimisation simultaneously. A realistic case study of sago value chain is solved to illustrate the developed approach.

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2. Problem Statement

A set of sago plantation $g \in G$ is given with area, A_g. The area of plantation g is converted into sago palm via conversion rate of V_g. Sago palm is then converted into a set of raw material $m \in M$ via conversion rate of $V_{g,m}$. The raw material is given flowrate and weight of $X_{g,m}$ and $q_{g,m}$, respectively. These raw materials are then supplied to a set of sago mills $f \in F$ which having capacity of $Z_{m,f,g}$ with flowrate of $X_{m,f,g}$ to produce a set of products $p \in P$ based on the conversion rate of $V_{m,f,g}$. The products are then transferred from sago mills f to a set of port $j \in J$ with flowrate of $X_{f,p,j}$. The port capacity is given as Z_j and total flowrate to port j is given as $X_{p,j}$. The stored products in port j are then shipped to a set of customer $u \in U$ with flowrate of $X_{p,j,u}$ based on the demand of customers ($D_{u,p}$). In order to identify the optimum pathway with minimum total operation cost and total life cycle risks of sago value chain, a Mixed Integer Linear Programming (MILP) approach is used for the formulation of the following mathematical models.

3. Life Cycle Optimisation Formulation

3.1 Mass Balances

$$A_g . V_g \geq \frac{X_{g,m}}{V_{g,m}} \qquad \forall g \forall m \qquad (1)$$

$$X_{g,m} = \sum_{f=1}^{F} X_{g,m,f} \qquad \forall g \forall m \qquad (2)$$

$$Z_{m,f,p} \geq \sum_{g=1}^{G} X_{g,m,f} . q_{g,m} . V_{m,f,p} \qquad \forall m \forall f \forall p \qquad (3)$$

$$\sum_{m=1}^{M} X_{m,f,p} = \sum_{j=1}^{J} X_{f,p,j} \qquad \forall m \forall f \forall p \forall j \qquad (4)$$

$$Z_j \geq \sum_{p=1}^{P} \sum_{f=1}^{F} X_{f,p,j} \qquad \forall j \qquad (5)$$

$$X_{p,j} = \sum_{u=1}^{U} X_{p,j,u} \qquad \forall p \forall j \qquad (6)$$

$$D_{u,p} = \sum_{j=1}^{J} X_{p,j,u} \qquad \forall u \forall p \qquad (7)$$

3.2 Cost Computations

$$C_g^{\text{Harv}} = UC_g^{\text{Harv}} . H_g \qquad \forall g \qquad (8)$$

$$C_{g,m,f}^{\text{Tran}} = UC^{\text{Tran\_road}} . d_{g,f} . n_{g,m,f}^{\text{Tran}} \qquad \forall g \forall m \forall f \qquad (9)$$

$$C_f^{\text{RMat}} = X_{g,m,f} . UC_{\text{g,m}}^{\text{RMat}} \qquad \forall f \qquad (10)$$

$$C_{f,p,j}^{\text{Tran}} = UC^{\text{Tran\_road}} . d_{f,j} . n_{f,p,j}^{\text{Tran}} \qquad \forall f \forall p \forall j \qquad (11)$$

$$C_j^{\text{Tran\_Port}} = \sum_{p=1}^{P} \sum_{u=1}^{U} UC_j^{\text{Tran\_Port}} . n_{p,j,u}^{\text{Tran}} \qquad \forall j \qquad (12)$$

$$C_{j,u}^{\text{Tran\_Sea}} = \sum_{p=1}^{P} \text{UC}_{j,u}^{\text{Tran\_Sea}} \cdot \frac{n_{p,j,u}^{\text{Tran}}}{n^{\text{CPT}}} \qquad \forall j \forall u \qquad (13)$$

$$C_{m,f,p}^{\text{Process}} = \text{UC}_{m,f,p}^{\text{Process}} \,.\, X_{m,f,p} \qquad \forall m \forall f \forall p \qquad (14)$$

$$TotC = \sum_{g=1}^{G} C_g^{\text{Harv}} + \sum_{g=1}^{G}\sum_{m=1}^{M}\sum_{f=1}^{F} C_{g,m,f}^{\text{Tran}} + \sum_{f=1}^{F} C_f^{\text{RMat}} + \sum_{f=1}^{F}\sum_{p=1}^{P}\sum_{j=1}^{J} C_{f,p,j}^{\text{Tran}} + \sum_{j=1}^{J} C_j^{\text{Tran\_Port}} + \sum_{j=1}^{J}\sum_{u=1}^{U} C_{j,u}^{\text{Tran\_Sea}} + \sum_{m=1}^{M}\sum_{f=1}^{F}\sum_{p=1}^{P} C_{m,f,p}^{\text{Process}} \qquad (15)$$

3.3 Risk Computations

$$R_g^{\text{Harv}} = \text{r}_g^{\text{Harv}} \,.\, H_g \qquad \forall g \qquad (16)$$

$$R_{g,m,f}^{\text{Tran\_Plant\_Mill}} = \sum_{y}^{Y} \text{r}_y^{\text{Tran}} \,.\, \text{d}_{g,y,f} \,.\, n_{g,m,f}^{\text{Tran}} \qquad \forall g \forall m \forall f \qquad (17)$$

$$R_f^{\text{Process}} = \sum_{p=1}^{P} \frac{X_{f,p}}{1{,}000} \,.\, \text{r}_f^{\text{Process}} \qquad \forall f \qquad (18)$$

$$R_{f,p,j}^{\text{Tran\_Mill\_Port}} = \sum_{y}^{Y} \text{r}_y^{\text{Tran}} \,.\, \text{d}_{f,y,j} \,.\, n_{f,p,j}^{\text{Tran}} \qquad \forall f \forall p \forall j \qquad (19)$$

$$R_j^{\text{Port}} = \frac{X_j}{1{,}000} \,.\, \text{r}_j^{\text{Port}} \qquad \forall j \qquad (20)$$

$$R_{j,u}^{\text{Sea}} = \sum_{p=1}^{P} r^{Sea} \cdot \frac{n_{p,j,u}^{\text{Tran}}}{n^{\text{CPT}}} \,.\, \text{d}_{j,u} \qquad \forall j \forall u \qquad (21)$$

$$TotR = \sum_{g=1}^{G} R_g^{\text{Harv}} + \sum_{g=1}^{G}\sum_{m=1}^{M}\sum_{f=1}^{F} R_{g,m,f}^{\text{Tran\_Plant\_Mill}} + \sum_{f=1}^{F} R_f^{\text{Process}} + \sum_{f=1}^{F}\sum_{p=1}^{P}\sum_{j=1}^{J} R_{f,p,j}^{\text{Tran\_Mill\_Port}} + \sum_{j=1}^{J} R_j^{\text{Port}} + \sum_{j=1}^{J}\sum_{u=1}^{U} R_{j,u}^{\text{Sea}} \qquad (22)$$

3.4 Fuzzy Optimisation of Objectives

$$\frac{\text{TotC}^{\text{UL}} - TotC}{\text{TotC}^{\text{UL}} - \text{TotC}^{\text{LL}}} \geq \lambda \qquad (23)$$

$$\frac{\text{TotR}^{\text{UL}} - TotR}{\text{TotR}^{\text{UL}} - \text{TotR}^{\text{LL}}} \geq \lambda \qquad (24)$$

$$\text{Max } \lambda \qquad (25)$$

4. Case Study

In this work, a case study of sago value chain in Sarawak, Malaysia is developed. Figure 1 shows the superstructure of sago value chain. It is consists of plantations, raw materials, sago mills, products, ports and customers. Based on the statistic (Department of Agriculture Sarawak, 2014), the sago palm is mainly grown in Mukah and Betong divisions in Sarawak. In this case, the major four districts (e.g., Mukah, Dalat, Saratok and Betong) are identified as plantation areas. In these plantations, the sago palm is harvested to produce sago logs as raw material. These sago logs are then sent to sago mills for sago starch production. As sago mills in Sarawak are located in Mukah, Dalat and Pusa districts, thus, two sago mills in Mukah and three sago mills in Dalat and one sago mills in Pusa are located as the sago mills for analysis. The produced sago starch is then sent to the three ports (e.g., Kuching port, Sibu port and Miri port) in Sarawak for storage before exporting to customers (e.g., Japan, Peninsular Malaysia, Singapore and Thailand) based on the customers' demand. In this case, Cost of Insurance and Freight (CIF) term is used as shipment term for sago starch delivery.

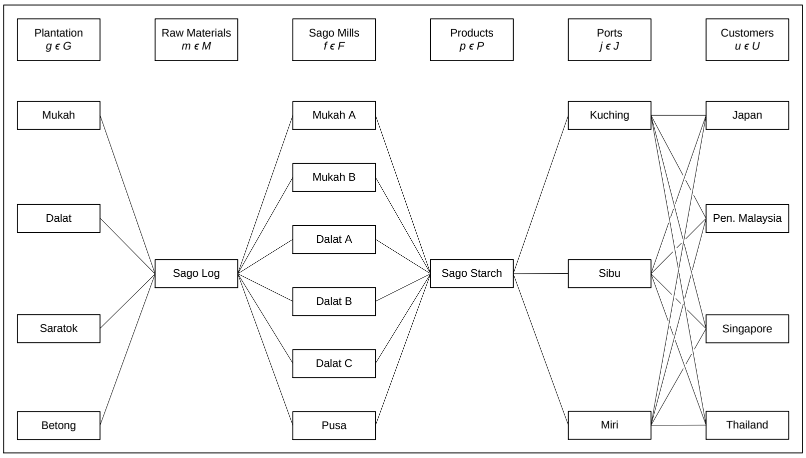

Figure 1: Superstructure of sago value chain

In order to determine the optimum total operating cost and total life cycle risks, the vital information is given in Tables 1 – 3. Table 1 shows plantation capacity, sago mills processing capacity and ports capacity as well as customers demand. Table 2 shows the unit cost of sea-freight to customers, port's charges, harvesting in plantations, sago starch processing of sago mills and selling prices of sago log. Table 3 shows the death (D), non-permanent disability (NPD), permanent disability (PD) risk of road accident, sea-freight, forestry and logging, sago starch processing and ports handling. Solving the Equations (1) – (25) in Mixed Integer Linear Programming (MILP) model with commercial optimisation software, LINGO, version 13, with Global Solver, optimum pathway of sago value chain is identified. Results of this case study is summarised in Table 4 and Figure 2.
Based on the optimised results shown in Table 4, the optimum pathway with maximum λ of 0.46 is identified. Note that the targeted minimum total operating cost is given as 8.992 x 10^7 MYR/y with minimum risk of 19,370 x 10^{-6} D/y, 146,142 x 10^{-6} NPD/y and 5,560 x 10^{-6} PD/y. The optimum pathway with mass flowrate is shown in Figure 2.

Table 1: Plantation capacity, sago mills processing capacity, ports capacity and customers demand

Plantation	Area Capacity A_g (ha)	Sago Mills	Processing Capacity, $Z_{m,f,p}$ (t/y)	Ports	Port Capacity, Z_j (t/y)	Customer	Demand $D_{u,p}$ (t/y)
Mukah	2,599	Mukah A	13,200	Kuch	7,000,000	Japan	13,000
Dalat	17,541	Mukah B	8,250	Sibu	450,000	P. M'sia	30,700
Saratok	1,907	Dalat A	7,260	MIri	53,900	Singapo	3,000
Betong	3,776	Dalat B	8,250			Thailand	1,300
		Dalat C	8,250				
		Pusa	3,960				

Table 2: Unit cost of sea-freight, road transportation, ports charges, raw materials, harvesting and sago starch processing

	Japan, $UC_{j,u}^{Tran\_Sea}$ (MYR/trip)	P. Malaysia, $UC_{j,u}^{Tran\_Sea}$ (MYR/trip)	Singapore, $UC_{j,u}^{Tran\_Sea}$ (MYR/trip)	Thailand, $UC_{j,u}^{Tran\_Sea}$ (MYR/trip)	Ports charges, $UC_{j}^{Tran\_Port}$ (MYR/container)
Kuch	3,960	1,650	1,485	2,640	1,500
Sibu	3,729	1,980	1,584	2,805	1,300
Miri	3,531	2,310	1,650	2,970	1,200

	Log selling price, $UC_{g,m}^{RMat}$ (MYR/log)	Harvesting Cost, UC_{g}^{Harv} (MYR/palm)
Mukah	10	3.8
Dalat	12	4.2
Saratok	8	3.0
Betong	9	3.6
Road Transportation cost, UC^{Tran_road} (MYR/km)	4.5	

	Processing Cost, $UC_{m,f,p}^{Process}$ (MYR/t)
Mukah A	296
Mukah B	303
Dalat A	305
Dalat B	300
Dalat C	310
Pusa	278

Table 3: Death (D), non-permanent disability (NPD) and permanent disability (PD) risk of road accident, sea-freight, forestry and logging, sago processing and port handling

Road accident risk, $r_y^{Tran} \times 10^{-14}$

	D/km	NPD/km	PD/km
Kuching	156	239	234
Samarahan	2.78	13.9	2.78
Serian	27.8	19.5	100
Simunjan	8.34	2.78	75.1
Sri Aman	103	97.3	8.34
Betong	27.8	8.34	22.2
Saratok	16.7	2.78	58.4
Sarikei	47.3	91.8	111
Maradong	0.00	0.00	0.00
Sibu	114	0.00	2.78
Dalat	2.78	13.9	2.78
Mukah	27.8	8.34	22.2
Tatau	33.4	8.34	16.7
Bintulu	139	13.9	50.1
Miri	186	114	656

Sea freight Risk, $r^{Sea} \times 10^{-15}$

D/nm	2.21

Forestry and logging Risk, $r_g^{Harv} \times 10^{-9}$

	D/palm	NPD/palm	PD/palm
Mukah	26.9035	231.265	8.54901
Dalat	69.8603	600.525	22.1992
Saratok	5.45857	46.9223	1.73455
Betong	10.2128	87.7901	3.24528

Processing Risk, $r_f^{Process} \times 10^{-8}$

	D/ton	NPD/ton	PD/ton
Mukah A	2.63	38.7	4.35
Mukah B	2.63	38.7	4.35
Dalat A	3.23	47.5	5.34
Dalat B	3.23	47.5	5.34
Dalat C	3.23	47.5	5.34
Pusa	6.57	96.6	10.9

Port Handling Risk, $r_j^{Port} \times 10^{-8}$

	D/ton	NPD/ton	PD/ton
Kuching	16.4	100	1.54
Sibu	28.2	172	2.64
Miri	24.7	151	2.31

Table 4: Case study results

	λ	*TotC* (MYR/y x 10^7)	$TotR^D$ (D/y x 10^{-6})	$TotR^{NPD}$ (NPD/y x 10^{-6})	$TotR^{PD}$ (PD/y x 10^{-6})
Min = *TotC*	-	8.821	20,516	153,251	5,678
Min = $TotR^D$	-	9.139	18,035	140,673	5,677
Min = $TotR^{NPD}$	-	9.139	18,403	140,025	5,452
Min = $TotR^{PD}$	-	9.139	18,897	142,638	5,424
Min = *λ*	0.46	8.992	19,370	146,142	5,560

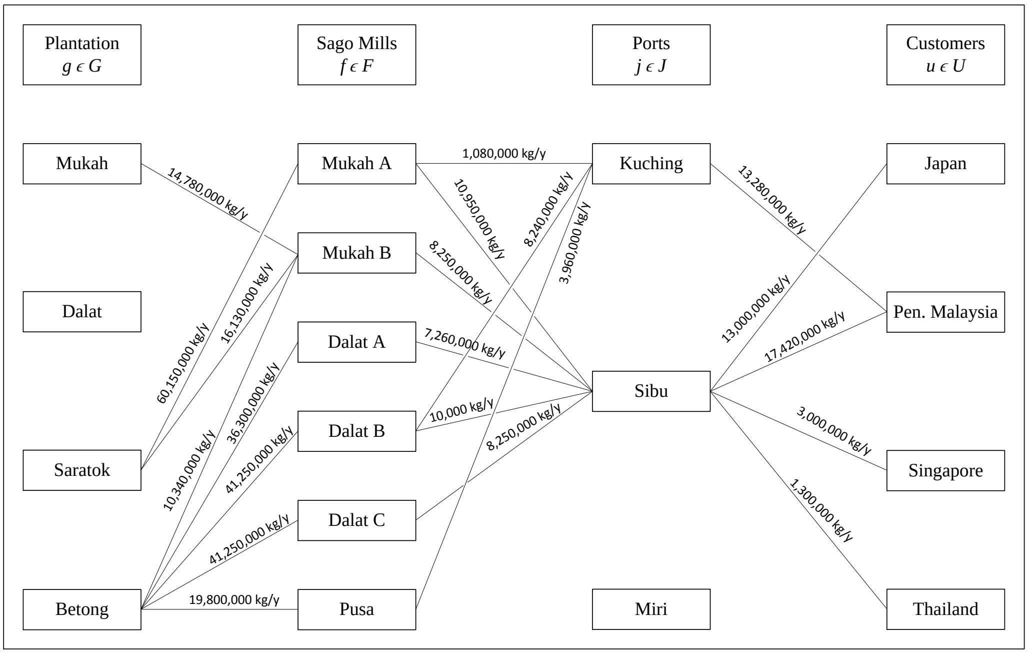

Figure 2: Optimum pathway of sago value chain

5. Conclusions

This paper presents a life cycle optimisation (LCO) approach which can identify the optimum pathway of sago value chain with minimum total operating cost and total life cycle risks via fuzzy optimisation. This work can be further extended in future with consideration of environmental aspects (e.g., carbon and water footprint). In addition, integration of sago-based biorefinery into sago value chain can also be conducted.

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