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Targeting Anchor Process via Cooperative Game-Based Optimisation Approach Within Integrated Palm Oil-Based Complex

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Recent threats to sustainability in the palm oil milling industry such as methane emissions, has impacted the palm oil market negatively. To facilitate methane emission mitigation, most palm oil mills opt for expensive biogas facilities. An alternative solution to this expensive biogas facility, can be an integrated palm oil-based complex (POBC). POBC is proposed to reduce environmental consequences while maximising the palm oil mill profit by integrating it with a palm oil refinery and implementing POME elimination strategy. However, in order to understand the feasibility of the POBC, it is important to identify the most crucial process otherwise known as the anchor process. The anchor process can be determined based on the allocation of incremental economic benefits among the internal processes. On that account, in work proposes a new process-level performance allocation approach based on cooperative game theory to investigate future optimisation strategies for the POBC. Cooperative game theory was previously applied for rationally allocating incremental profits among collaborating parties and determining anchor tenant within an eco-industrial park. In this study, the cooperative game model analyses internal processes instead of collaborating plants to determine the anchor process. The anchor process is critical for defining performance benchmarks for other processes within the POBC. The developed framework is applied consecutively on the given POBC case study based on the presented framework. The optimal results obtained are analysed to determine the anchor process for deciding suitable strategies to improve the overall profitability of POBC.

1. Introduction

To effectively break the environmental and social barrier of the palm oil supply chain in Malaysia, the government has announced the compulsory implementation of the Malaysian Sustainable Palm Oil (MSPO) certification for all palm oil mills (POMs) effective January 2020 (Palansamy and Dzulkifly, 2020). In this respect, palm oil smallholders require sustainable solutions to improve environmental aspects at the POMs. One significant challenge to this is the management of palm oil mill effluent (POME). POME is responsible for large amounts of greenhouse gas (GHG) emissions. These emissions are caused by biogas that is released when POME is treated in anaerobic digestion (AD) systems at the POM. To solve this issue, some POMs have considered expensive biogas recovery systems. Apart from biogas recovery, Tan et al. (2020) studied the feasibility of integrating an alternative POME management method, known as POME elimination, into an integrated palm oil-based complex (POBC). The design of POBC process route considers FFB pre-treatment, conventional and undiluted palm oil extraction, conventional heat and power (CHP), biogas recovery, POME evaporation and palm oil refining processes. The developed model successfully provided economic potential (EP) maximised POBC design to convert fresh fruit bunches (FFB) into refined palm oil products with POME elimination strategy implemented for mitigating biogas release. For the planning of a new system as mentioned above, optimal flowsheets are designed using previously published optimisation approaches could not demonstrate the necessity of each process and the flexibility in flowsheet modification. This could lead to owners wasting

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resources by investing in non-critical process or removing significant processes that may cause great economic loss for future plant retrofit or technology advancement. To address this concern, it is desired to evaluate the impact of each process towards the overall plant performance. Doing this will allow opportunities to discover potential process improvements for the designed system. The challenge is to develop a suitable methodology and tool to rationally distribute the total system contributions among interconnecting processes. It is suggested in this study that the cooperative game-based optimisation approach can be applied to perform the abovementioned task. Previous studies have been utilised cooperative game theory to demonstrate economic savings allocation between collaborating parties within Eco-industrial Parks (EIP) such as a palm oil EIP (PEIP) (Tan et al., 2016). Andiappan et al. (2015) attempted cost savings distribution among collaborating POM, Biomass-Based Trigeneration System (BTS) and Palm Biomass Biorefinery (PBB) of different ownerships using the cooperative game model developed by Maali (2009). Andiappan et al. (2018) extended his work to perform rational allocation of incremental benefits among stakeholders in a PEIP with stability analysis included. Previous works have only considered cooperative game-based profit allocation between individual plants for industrial symbiosis and did not address the importance of internal processes. Cooperative game models assume that “players” in a given “game” are willing to compromise and collaborate. Such context is suitable for describing interdepending processes within a system. Essentially, internal processes within the POBC can serve as multiple “players” responsible for the overall performance of the “game” and the pooled impacts could be rationally distributed among the processes using cooperative game model. To date, no study has performed process level profitability allocation based on cooperative game theory to allocate economic contribution among internal processes within a conceptual complex. There is a need to determine the anchor process, i.e., the process which provides the greatest contribution to the economic performance of POBC. This study presents a novel cooperative game-based economic performance allocation framework within a sustainable POBC designed using multi-objective optimisation. The developed mathematical models aim to address the research gap in distributing profitability among POBC interconnecting processes, prior to determining the newly defined “anchor process”. The optimal results should provide insights for the POM owners on POM retrofit and rational budget distribution for POBC process maintenance and advancement. Investment on the anchor process is suggested to maximise the profitability enhancement of the POBC flowsheet. Without identifying the anchor process, it may lead to the company focusing on improving the non-critical process and wasting resources.

2. Problem Statement

The problem statement formulated for the cooperative game-based optimisation and economic performance allocation approach is as below:

- Given a set of resources *i* and potential technologies *p* in a process (i.e., palm oil milling technologies, biomass-to-energy conversions and biogas applications), economic data, process and operating data for each technology, environmental data, the optimal flowsheet of POBC is generated via fuzzy optimisation subject to multiple objectives such as economic performance (EP), net energy, greenhouse gas (GHG), land and water footprint (WFP) to ensure POBC sustainability.
- Based on the optimal POBC flowsheet obtained from fuzzy optimisation, a set of internal process stages *f* which consists of one or more technology *p*, is defined. Each scenario *z* is formed by a group of functioning process stages *f* to describe different process failure possibilities and inter-process coalition within the POBC.
- The characteristic function *v(z)* is defined as the overall benefits contributed by all process stages *f* working together in scenario *z*. The values of *v(z)* are obtained according to the description in Section 3.2.
- The final objective is to perform optimal allocation of economic contribution among process stages *f* via the adapted cooperative game model proposed by Maali (2009) and subsequently determine the anchor process for gross profit (GP) enhancement.

3. Methodology

The proposed optimisation framework for cooperative game-based economic performance allocation among internal processes within a POBC is described as follows. In Stage 1, fuzzy optimisation approach is applied to generate the optimal and sustainable design of POBC with multi-objective concerns. Subsequently in Stage 2, the optimum flowsheet of POBC generated from Stage 1 is evaluated to distribute the selected processes into significant process stages and model all possible process stage failure scenarios within the POBC. The cooperative game-based performance allocation approach is then performed in Stage 3. Essentially, the cooperative game model developed by Maali (2009) is used to rationally allocate the overall economic performance among internal process stages identified and optimal results obtained from Stage 2. Lastly, the optimal allocation results are analysed and discussed to identify the anchor process for overall POBC profitability enhancement in Stage 4. In this context, the anchor process would be the process that is allocated the largest percentage of GP contribution to the POBC among all internal processes in the optimal flowsheet generated. By advancing the technology for anchor process in the future, the profitability of the POBC can be improved more effectively. On the other hand, failure of the anchor process will cause the greatest loss to the POBC revenue the process requires additional caution in maintenance or back up equipment.

3.1 Fuzzy multi-objective optimisation model

The optimal POBC design to be input into the cooperative game model is obtained by solving the fuzzy multi-objective optimisation model adapted from the work of Tan et al. (2020a) with the incorporation of net energy (*EGBAL*), GHG balance (*GHGBAL*), WFP (*TWFP*), land footprint (*LFP*) constraints calculated via Eq(1)-(4).

$$EGBAL = PRO_{i=32} + ELEC^{EXCESS} - ELEC^{EX} \tag{1}$$

$$\begin{aligned} GHGBAL = (\sum\nolimits_i Ref_{i,p}^{GHG} \times MAT_{i,p} + \sum\nolimits_i Ref_{i,p}^{GHG} \times SGRES_{i,p}) + \sum\nolimits_i Rind_i^{GHG} \times EXRES_i \\ - \left(Rind_{i=32}^{GHG} \times PRO_{i=32}\right) + \left(Rind_{i=31}^{GHG} \times ELEC^{EX}\right) + \left(Rind_{i=2}^{GHG} \times PRO_{i=2}\right) \end{aligned} \tag{2}$$

$$TWFP = EXRES_{i=24} + EFF(\frac{C^{eff} - C^{act}}{C^{max} - C^{nat}}) \tag{3}$$

$$LFP = \sum\nolimits_p LANDF_p \times cap_p \tag{4}$$

3.2 Cooperative game performance allocation model

The objective of the cooperative game model is to perform optimal allocation of economic contribution among internal process stages *f* within the optimal POBC flowsheet obtained from fuzzy optimisation. Before performing the inter-process incremental profit allocation, the available processes *p* in the given optimum flowsheet are grouped to define a set of significant process stages *f* (f = 1, 2, 3,…F) and all possible failure scenarios *z* (*z*=1, 12, 123, …, 123…F) considering various combinations of functioning process stages *f*. The characteristic function *v(z)* for POBC economic performance allocation is defined as the GP savings in scenario *z* compared to stand-alone operations (GP_z^{save}) to demonstrate the individual contribution of each process stage *f* in improving the overall GP of the POBC. It can be calculated from Eq.(5) for every scenario *z* using Excel Spreadsheet. In Eq(5), a set of basis process stage *u* is defined for each scenario *z* as a subset of process stages *f* for calculating GP_z, which is the GP generated for those scenario *z* that include process stage *u*. GP_u represents the GP for solely operating basis process stage *u* based on case study. According to Eq.(5), it is essential to obtain the maximum GP for set *z* to calculate *v(z)*. The challenge in calculating the optimum GP for all process stage failure scenarios *z* lies in the interdependency of internal processes compared to collaborating plants. Initially, specific superstructure and modelling are required for each scenario to calculate the respective *v(z)*. To simplify the task, a generic optimisation model is proposed to obtain optimal results for different scenario *z* by alternating specific input parameters when solving the model subject to GP maximisation. The fuzzy optimisation model is adapted to formulate the mono-objective optimisation model by removing the fuzzy constraints and integrating Eqs.(6)-(9). Binary indicators $Pind_p^{EXIST}$, $Pind_p^{BYPASS}$ and $Pind_p^{RELATE}$ are defined to determine the existing, by-passing and correlated processes in each scenario z. The existing and by-passing processes represent the functioning and non-functioning processes. The correlated process is defined as the basis process to calculate the intermediate resource flow when the correlated process between two functioning processes fails. For the failure of each process stage *f*, the binary parameters for unconsumed by-product (RES_i^{POL}) and externally processed intermediate material ($MAT_{i,p}^{EXT}$), other parameters such as the purchasable amount ($RES_{i,p}^{PEXT}$) and unit external processing cost ($UCOST_i^{EXT}$) for the intermediate materials are identified. The amount of available external resource ($AVRES_i$) considering process failure is calculated by summing the general resource availability ($AVRES_i^{LOCAL}$) and the external intermediate resource availability ($RES_{i,p}^{PEXT}$) with respect to different process failure ($Pind_p^{BYPASS} = 1$) as indicated in Eq(6). The generic material conversion matrices for POBC process input and output are defined as $MCM_{i,p}$ and $PRCM_{i,p}$. For process failure scenarios, by-passing resource conversion indices $MCM_{i,p}^{BY}$ and $PRCM_{i,p}^{BY}$ are considered to exclude the by-product production and utility consumption of failing process during calculation. In Eq(7), the binary parameter for general process conversion ($PRCM_{i,p}^{NORMAL}$) and $Pind_p^{RELATE}$ are multiplied with $PRCM_{i,p}$ to obtain the final material conversion for calculating the exact amount of resource to be externally processed when the correlated processes *p* ($Pind_p^{RELATE} = 1$) in between two functioning processes *p,* fails in a continuous process route. $PRCM_{i,p}^{BY}$ is subtracted from $PRCM_{i,p}$ to omit the generation of by-products for by-passed processes

($Pind_p^{BYPASS} = 1$). Similarly in Eq(8), $MCM_{i,p}^{BY}$ is subtracted from $MCM_{i,p}$ in calculating the total amount of processing material in process *p* ($PRES_p$) to eliminate the specific input utility for by-passing processes. This is to ensure that the utility cost and by-product revenue of failing processes are not considered in the GP calculation. Finally in Eq(9), the overall external processing cost is calculated by summing the total cost for processing intermediate materials and cost for treating unconsumed by-products such as POME. The total amount of intermediate material to be processed externally is obtained by multiplying the binary parameters $MAT_{i,p}^{EXT}$ and $Pind_p^{BYPASS}$ to the sum of self-generated resource ($SGRES_{i,p}$) calculated in relation to Eq(7). By modifying the values of related parameters in Eq(6)-(9), the optimal GP results for different scenario *z* can be obtained by solving the formulated MILP optimisation model. Subsequently, the values of *v(z)* are calculated using Excel Spreadsheet.

$$GP_z^{save} = GP_z - GP_u \qquad \forall\, z \ni u \quad \forall\, u \subseteq f \tag{5}$$

$$AVRES_i = AVRES_i^{LOCAL} + \sum\nolimits_p RES_{i,p}^{PEXT} \times (Pind_p^{BYPASS}) \qquad \forall i \tag{6}$$

$$SGRES_{i,p} = PRES_p \times PRCM_{i,p}^{NORMAL} \times Pind_p^{RELATE} \times (PRCM_{i,p} - (PRCM_{i,p}^{BY} \times Pind_p^{BYPASS})) \quad \forall i\ \forall p \tag{7}$$

$$MAT_{i,p} = (MCM_{i,p} - (MCM_{i,p}^{BY} \times Pind_p^{BYPASS})) \times PRES_p \qquad \forall i\ \forall p \tag{8}$$

$$COST_i^{EXT} = UCOST_i^{EXT} \times \sum\nolimits_p SGRES_{i,p} \times [(MAT_{i,p}^{EXT} \times Pind_p^{BYPASS}) + (RES_i^{POL})] \qquad \forall i \tag{9}$$

According to Maali's (2009), the specific weightage of each "player" in a cooperative game can be calculated based on the values of characteristic function for all collaborating scenario. In this study, the weightage of economic performance allocation for each process stage *f* is given as W_f and can be calculated via Eq(10) using Excel Spreadsheet. Variable $v(z - \{f\})$ is defined as the value of characteristic function achieved by the working processes in scenario *z* with the exclusion of process stage *f* and $v_c(\aleph)$ describes the scenario where all process stages within the POBC are working without failure. The calculated *v(z)* and W_f results are then inputted into the cooperative game allocation model adapted from the work of Maali (2009) to optimise the economic performance allocation (ALL_{f}) among process stages within the fuzzy optimum POBC via Eq(11)-(13). The percentage performance allocation of each process stage is denoted as $PALL_f$ in Eq(14) which reflects the process stage's degree of contribution towards the overall POBC performance. The cooperative game optimisation model is solved by maximising variable λ as in Eq(15). The optimal results are then analyzed to determine the anchor process for POBC profitability which is the process with the largest value of $PALL_f$.

$$W_f = \frac{\sum_z v(z) - v(z - \{f\})}{v(\aleph)} \qquad \forall f \tag{10}$$

$$\frac{1}{W_f} ALL_f \geq \lambda \qquad \forall f \tag{11}$$

$$ALL_{\mathrm{f}} \geq v(\{f\}) \qquad \forall f \tag{12}$$

$$\sum\nolimits_f ALL_f = v(\aleph) \tag{13}$$

$$PALL_f = \frac{ALL_{\mathrm{f}}}{v(\aleph)} \qquad \forall f \tag{14}$$

$$Maximise\ \lambda \tag{15}$$

4. Case study

The proposed optimisation and process-level performance allocation framework is applied to a case study based on the work of Tan et al. (2020b) and literature. A palm oil enterprise aims to retrofit its POM into a POBC to reduce methane emission by integrating with a POR situated beside the POM. The POM conventionally consumes 60 t/h of FFB for 4,350 h/y. By integrating with POR, CPO extracted can be further processed into Refined, Bleached, Deodorised Palm Olein (RBDPOL), Refined, Bleached, Deodorised Palm Stearin (RBDPS) and Palm Fatty Acid Distillate (PFAD). Two methane mitigation strategies namely POME elimination and biogas recovery are to be selected for the POBC process route design. The operational life span of the POBC is assumed to be 15 y. The optimal design of POBC is to be done subject to maximum EP and net energy as well as minimum GHG, water and land footprints. In addition to process flowsheet optimisation, the palm oil enterprise would like to analyse the optimal POBC design to identify the potential anchor process within the proposed system that can drive the POBC profitability. The anchor process serves as the performance benchmark of the system with the highest positive influence on the profitability of POBC.

5. Results and discussion

The optimal flowsheet of POBC with sustainability concerns as illustrated in Figure 1 is obtained by solving the case study via the developed fuzzy multi-objective optimisation model in the General Algebraic Modelling System (GAMS) software (version 24.7.4) using the CPLEX solver (12.6.3.0). POME elimination approach is applied with POME evaporation and undiluted clarification technologies selected. Sequential batch reactor (SBR) is installed for separate palm oil refinery effluent (PORE) treatment to reduce steam consumption for POME evaporation while compromising additional CPO recovery.

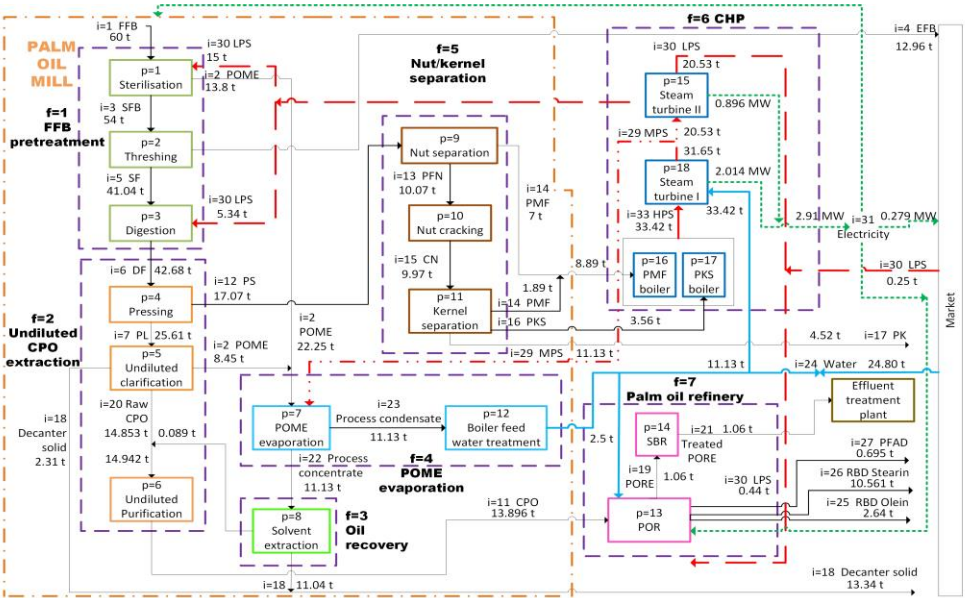

Figure 1: Fuzzy optimal flowsheet for multi-objective POBC

Seven process stages *f* are identified according to the selected process units in the POBC optimal flowsheet as shown in Figure 1 including FFB pretreatment, undiluted CPO extraction, oil recovery, POME evaporation, nut/kernel separation, CHP system and POR. All 127 possible process failure scenarios *z* are defined with related parameters assigned to model each scenario. Optimal allocation of process stage contribution to the overall GP is performed via the developed models in Section 3.2 and solved in GAMS with similar solver. The optimal allocation results are summarised in Table 1. Based on the results, the determination of anchor process with respect to the profitability of POBC is done. In this study, the anchor process is the process which attains the highest percentage of GP contribution. 34.39 % of pooled GP savings are distributed to the nut/kernel separation stage as the anchor process for POBC profitability. This is due to its contribution to fibre and shell production which is the essential feed for the CHP system to satisfy POBC energy demand and attractive revenue from selling palm kernel. If the nut/kernel separation process stage fails or has been uninstalled, the palm oil enterprise will suffer a great loss of revenue that lowers the economic feasibility of the new POBC scheme implementation. Investment for advancing the kernel separation technology such as yield improvement will provide the greatest economic improvement for future optimisation of POBC. The FFB pretreatment stage rated second in GP contribution by producing empty fruit bunches (EFB) and saving expensive external operating cost. The attractive profitability improvement of 13.94 % from POR suggests economic favourability in integration between POM and POR within the POBC. The results from this work are compared with the reported literature in Table 2. The anchor process identified for this work, nut/kernel separation is in fact one of the process stages in POM, which is the anchor plant identified for previous works.

Table 1: Summarised optimal results for economic performance allocation

f	Process stage	GP contribution allocation (%)	Anchor process
1	FFB pretreatment	23.30	
2	Undiluted CPO extraction	18.59	
3	Oil recovery	3.40	
4	POME evaporation	1.28	
5	Nut/kernel separation	34.39	√
6	CHP system	5.10	
7	POR	13.94	

Table 2: Results comparison between work and literature

Literature	Tan et al. (2016)	Andiappan et al. (2015)	Andiappan et al. (2018)	This study
Anchor plant/process	POM	POM	POM	Nut/kernel separation in POM
Savings allocation (%)	47.81	45	48	34.39
POR consideration	×	×	×	√
Evaluation level	Plant	Plant	Plant	Process stage

6. Conclusions

This work performed a rational allocation of economic performance within a new conceptual POBC via the novel cooperative game-based performance allocation framework. Fuzzy and cooperative game optimisation models are developed to optimise the POBC design for maximum profitability and minimum environmental footprints followed by distribution of economic benefits among internal processes to demonstrate the profit enhancement potential of each process stage. The economic anchor process within the POBC is determined based on the optimal allocation results to discover future profitability improvements opportunities of the POBC. It is concluded that the anchor process concerning POBC profitability is the nut/kernel separation stage with 34.39 % of GP contribution. The optimal POBC flowsheet could be considered by owners for POM retrofit and among the processes, more budget could be allocated for maintenance and technology advancement in the nut/kernel separation. The proposed framework and models could be easily revised to perform optimisation and process-level performance distribution during the planning phase of any sustainable system. Multi-objective performance allocation will be considered in the future work to evaluate the sustainability drivers within the POBC.

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