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A Systematic Decision Analysis Approach to Design Biomass Combined Heat and Power Systems

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Highlights of research

- Systematic design analysis framework to design combined heat and power systems is proposed
- This framework considers optimistic, pessimistic and cautious risk decision-making
- This framework combines Maximax, Maximin and Minimax Regret Criterion

Abstract

Designing a biomass combined heat and power (CHP) system that fulfils uncertain energy demands is a challenging task. This task becomes increasingly complex when historical data and probability distributions are not well defined. This work presents a newly developed decision analysis design framework for biomass CHP system which considers three types of decision-makers, namely optimistic, pessimistic and cautious decision-makers. To illustrate the proposed framework, a palm-based biomass CHP case study is solved. In addition, sensitivity analysis is performed to evaluate the effect of Feed-in Tariff (FiT) rates towards the design of CHP system. The optimum biomass CHP design is then further analysed to determine the “must-have”, “optional” and “must-avoid” equipment within a given range of power demand. The proposed decision analysis design framework enables decision makers to make informed decisions.

Keywords: Biomass**,** Combined Heat and Power, Maximax Criterion, Maximin Criterion, Minimax Regret Criterion

Nomenclature

Abbreviations

CAPEX	Capital Expenditures
CCHP	Combined Cooling, Heat and Power
CHP	Combined Heat and Power
CPKO	Crude Palm Kernel Oil
CPO	Crude Palm Oil
EFB	Empty Fruit Bunches
FFB	Fresh Fruit Bunches
FiT	Feed-in Tariff
LP	Linear Programming
MCS	Monte Carlo Simulation
MILP	Mixed-Integer Linear Programming
MINLP	Mixed-Integer Non-Linear Programming
MRC	Minimax Regret Criterion
MSW	Municipal Solid Waste

NLP	Non-Linear Programming
PKS	Palm Kernel Shell
PMF	Palm Mesocarp Fibre
POME	Palm Oil Mill Effluent
RET	Renewable Energy Technologies
SREP	Small Renewable Energy Power

Indices

i	Index for biomass
p	Index for primary product
p'	Index for final product
j	Index for conversion technology
j'	Index for energy generation technology
e	Index for energy produced
a	Index for capacity of CHP designed
b	Index for occurring energy demand

Variables

F_{ij}	Mass flow rate of biomass *i* entering technology *j*
F_{jp}	Mass flow rate of product *p* produced from technology *j*
F_{p}	Produced primary product *p* from technology *j*
$F_{pj'}$	Mass flow rate of primary product *p* distributed to technology *j'*

$F_{p'}$	Produced final product *p'* from technology *j'*
E_e^{T}	Total energy generated *e* by technology *j* and *j'*
E_e^{excess}	Excess energy generated *e* in terms of energy demand
$C_j, C_{j'}$	Cost of each technology *j* or *j'*
C^{Total}	Total cost of the biomass CHP design
P^{Gross}	Gross profit of the biomass CHP system
P_{ab}	Gross profit of the biomass CHP system in relative to capacity of CHP design *a* and energy demand *b*
$P_A^{\max}$	Highest gross profit attainable in relative to capacity of CHP design *a*
$P_A^{\min}$	Lowest gross profit attainable in relative to capacity of CHP design *a*
R_{ab}	Regret value of the biomass CHP system in relative to capacity of CHP design *a* and energy demand *b*
$R_A^{\max}$	Maximum regret value in relative to capacity of CHP design *a*
$(R_A^{\max})^{\min}$	Smallest maximum regret value in relative to capacity of CHP design *a*

Parameters

F_i	Total mass flow rate of biomass *i*
x_i	Component composition of biomass *i*
θ_{jp}	Conversion factor for each technology *j*
$\theta_{pj'}$	Conversion factor for each technology *j'*
n_{je}	Energy conversion factor of technology *j*

$n_{j'e}$	Energy conversion factor of technology *j'*
E_e^{demand}	Energy demand, *e* required to produce from Biomass CHP system
$k_j^{CAPEX}, k_{j'}^{CAPEX}$	Capital Expenditure Cost factor of technologies *j* or *j'*
$k_j^{OPEX}, k_{j'}^{OPEX}$	Operating Expenditure Cost factor of technologies *j* or *j'*
$Tariff_e^{demand}$	Feed-in Tariff charged on energy generated for energy demand *e*
$Tariff_e^{excess}$	Tariff rates charged on excess energy generated *e*
AOT	Annual Operation Time for the biomass CHP system
CRF	Annual capital recovery factor

1. Introduction

A biomass combined heat and power (CHP) system commonly consists of two types of units [1,2]. The first type of unit is the pre-treatment unit. Pre-treatment units typically include shredders and dryers. Such units are often essential to decrease size and moisture content of biomass in order to increase efficiency during combustion and conversion of biomass into intermediate products[3–5]. The second type of unit is the product conversion unit. Product conversion units refer to processes which convert biomass/intermediate products into energy or materials, i.e., boiler, gasification, digester, etc. In a conventional boiler, biomass is combusted to generate heat and produce high pressure steam. The generated steam is then converted into power via reduction of pressure in series of steam turbines. Meanwhile, gasification process converts biomass into syngas (mainly carbon monoxide, CO and hydrogen, H_2) at high temperatures (>800 °C). Besides, biomass can be broken down into biogas (mainly methane, CH_4 and carbon dioxide, CO_2) via microorganisms in anaerobic digestion. Note that both syngas and biogas can then be converted into power via power generation units, such as gas engines, gas turbines and micro-turbines[4,5]. Based on the abovementioned technologies, it is evident that there are many alternatives to design a biomass CHP system. Although a non-exhaustive list of alternatives can be beneficial, this large number of options presents a challenging task to design an optimal CHP system based on design capacity, gross profit, energy demand, biomass supply, etc. In this respect, Process Systems Engineering (PSE) can play an important role to address such challenge.

PSE is a research area focused on developing systematic design approaches to identify the optimum type, design and interconnection of processing units in a process system [6,7]. Among the approaches developed in the field of PSE are heuristic, insight-based and mathematical optimisation approaches [8–10]. However, only mathematical optimisation approaches for process synthesis and design of CHP are reviewed in this work. Mathematical optimisation approaches generally consists of several steps. Firstly, decision makers would compile all considered alternative process pathways, their respective unit operations and configurations. The compiled process pathways are then represented in a network of interconnections known as a superstructure [11]. A superstructure typically contains a detail account of all possible interconnections between process units. Next, design variables and parameters of each process unit (e.g., component, mass and energy flow rates, capital and operating expenditures, etc.) in the superstructure are mathematically modelled to correlate each other via mathematical equations[12]. Mathematical models can be generally categorised as linear programming (LP), non-linear programming (NLP), mixed-integer linear programming (MILP) and mixed-integer non-linear programming (MINLP). The objective function is defined along with the constraints for variables considered in the mathematical model. Objective functions are typically defined based on the requirement of decision maker (e.g., maximising economic performance, minimising environmental impact, etc.). By optimising the objective function in mathematical optimisation software, the optimum design can be determined[13,14].

As shown in literature [15–17], several mathematical optimisation approaches had been developed to design biomass CHP systems. For instance, Papadopoulos et al.[16] developed a computer-based framework which selected suitable CHP process units based on various types of lignocellulosic biomass (i.e., municipal solid waste (MSW), wheat, corn, cotton and sunflower). Sartor et al.[17] proposed a methodology to provide estimated data and optimise energetic, environmental and economic performances of a biomass CHP operating within a district heating network. The developed methodology[17] provided a simple model of a CHP plant which consists of thermodynamic, combustion and heat transfer simulations. However, Sartor et al.[17] only focused on estimating performance of a biomass boiler unit and its distribution of steam. Maria et al.[18] then proposed an alternative methodology to optimise the capacity of a CHP system using biomass-fired Organic Rankine Cycle (ORC) to produce heat and power. The developed mathematical model assessed thermal energy demand required in Spain and subsequently determined the optimum energy capacity of the CHP system based on different climates. It is important to note that this model[18] is highly dependent on the availability of thermal energy demand data for a given location. Hence, the model is not applicable to design a CHP system at new locations with scarce amount of thermal energy demand data. Besides, Bracco et al.[19] presented an alternative model to design and operate a CHP system with minimised capital costs, operational costs and CO_2 emission.

Based on the aforementioned contributions, it is observed that the proposed mathematical models focused on optimising the CHP design based on economic and environmental performance. However, it is worth noting that the previous works assumed steady-state scenarios when designing a CHP system. In reality, CHP operations vary due to fluctuating energy demands and other technical, economic and environmental uncertainties [20,21]. If these uncertainties are not considered during the design stage, the final designed CHP system would not be able to fulfil energy demand commitments and suffer from economic penalties.

Several works [22–28] have been proposed to consider uncertainties in the design of biomass CHP systems. For instance, Andiappan et al. [22] developed a multi-period optimisation approach to design biomass CHP systems based on uncertain biomass supply and energy demands. Andiappan et al.[23,24] further extended the previous work [22] to incorporate reliability, optimal sizing and operational strategy for biomass CHP systems. Besides, Andiappan et al.[25] developed an approach to analyse the effect of operational uncertainty for a biomass CHP system based on economic stability when operating within an eco-industrial park (EIP). Meanwhile, Teo et al.[26] proposed a multi-period optimisation model to synthesise a centralised biomass CHP for an EIP. The proposed model [26] considered uncertainties in biomass supply, energy demands and price of raw materials. In addition, other research contributions have accounted for the economic uncertainty in renewable energy technologies (RETs). Economic uncertainty refers to the potential loss of profit when the uncertainty is realised by RETs. To assess loss of profit, Monte Carlo Simulation (MCS) approaches are commonly used in previous works. MCS incorporates uncertainty by using the probability distribution of an uncertain variable to compute the possibility for a given condition to occur. For instance, Arnold et al.[28] evaluated economic uncertainty for RETs via MCS. For this work[28], MCS was used to compare different boundary conditions such as climate, capital and operating cost. The boundary conditions were assessed based on two criteria; system profitability and rate of return of investment (ROI). Furthermore, Edinaldo et al.[27] presented a comparable mathematical model that determines the worth of investing in the selected RET.

Some contributions have extended the loss of profit analysis to subsequently synthesise a CHP design. Yokoyama et al. [29] presented a Minimax Regret Criterion (MRC) approach to optimise CHP design with uncertain energy demand. The developed model [29] considered multiple design, demand and operational variables and generated an optimal design of equipment capacities based on annual total cost. Later, Yokoyama et al.[30] extended the previous study [29] by adding MRC approach into a MILP model, where uncertain energy demands are now expressed as intervals instead of fixed constants. The extended model compared performance of an energy supply system within an interval of uncertain energy demand with a conventional energy supply system. Subsequently, it provided a range of annual total cost for both systems considering various design, demand and operational variables. Both systems were then analysed using MRC approach to compare and select the CHP system with higher performance. Wang et al.[31] then presented an alternative MRC approach to optimise a combined cooling, heat and power (CCHP) system. Wang et al.[31] focused on risk in scheduling energy cycles of CCHP considering multiple energy sources which include natural gas, solar energy, geothermal energy and grid power.

Based on the aforementioned work, several observations were noted. Firstly, it is worth noting that most of the aforementioned works focused on analysing the performance biomass CHP systems based on operational and economic uncertainties. Meanwhile, it is also noted that MCS approaches were often used to evaluate potential loss of profit for CHP systems but not to clearly screen and select an optimal configuration of process units based on desired objectives (i.e. gross profit, environmental impact). For instance, Yokoyama et al. [29,30] used the MRC approach to evaluate loss of profit on an existing energy system and compare its performance with a conventional energy supply system. On the other hand, aforementioned works [29,30] assumed that the probabilities and historical information of varying energy demands are available prior to design. However, in reality, biomass CHP systems are not highly developed as compared to conventional natural gas CHP systems. Hence, there is a lack of historical data on energy demand variations for biomass CHP systems. As a result, probabilities of potential uncertainties tend to be unavailable. Despite the lack of data, decision-makers are still expected to make informed and risk-free decisions regarding the design of a biomass CHP system. In addition, decision-makers are commonly assumed as rational decision-makers that make the same level of judgements that provides the optimum CHP design. However, in a practical sense, there are several types of decision-makers; optimistic, pessimistic and cautious decision-makers [32]. The design of CHP system would then be heavily dependent on the decision-makers involved and their previous experiences. In this respect, it is important to develop a generic decision analysis design framework that incorporates different types of decision-makers when designing biomass CHP systems.

As such, this work proposes a systematic framework for designing biomass CHP systems based on Maximax Criterion, Maximin Criterion and Minimax Regret Criterion (MRC) respectively. The proposed framework provides a step-wise mathematical procedure that can be applied despite limited information on probabilities and historical data. In this work, Maximax Criterion refers to an optimist, or 'risk-seeking' investor. This type of decision-maker seeks to achieve the best results if the best happens [32,33]. In other words, if a decision-maker employs the Maximax Criterion, the best is assumed to happen. Maximin Criterion is suitable for a pessimist aiming to obtain the best results if the worst happens. In particular, pessimist decision-makers would look at the worst possible outcome and choose the outcome which is guaranteed to minimise losses[32,33]. Meanwhile, MRC is a useful strategy for a cautious or risk-neutral decision-maker. The term "regret" in MRC refers to the loss of profitable opportunity if a wrong decision was made during design [32]. Details of the three-aforementioned types of decision-makers are described further in the following section.

The next section describes a detailed account of the mathematical formulation involved in the proposed framework. An illustrative example is used to illustrate the proposed framework in the section after. Then, a detailed biomass CHP case study is solved via the proposed framework. Lastly, conclusions and future works are discussed.

2. Decision Analysis Design Framework

Figure 1 shows the developed decision analysis design framework. A detailed account of the developed framework is presented in the following sub-sections.

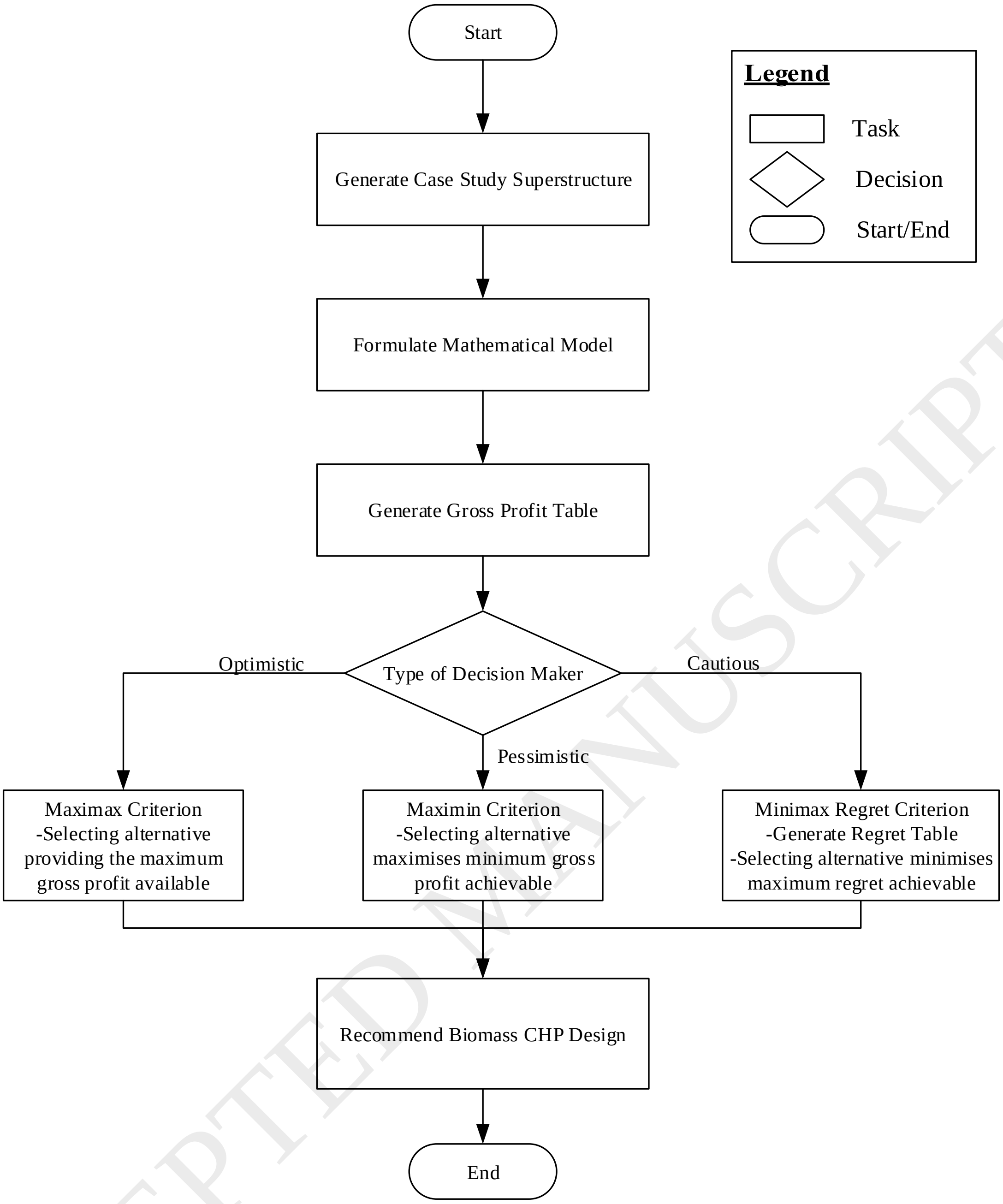

Fig. 1: Decision Analysis Framework

2.1 Developing Superstructure

According to the proposed framework, a generic superstructure is first developed as shown in Figure 2 [34]. As shown, resources $i \in I$ represents available supply of biomass with flow rates (F_i). F_i can be converted into primary product of $p \in P$ via technology $j \in J$. Primary product p

can then be converted into final product $p' \in P'$ via technology $j' \in J'$. On the other hand, biomass supply F_i and products p can be converted to energy of $e \in E$ through technologies $j \in J$ and $j' \in J'$ respectively to meet the energy demand occurring in scenario $b \in B$ with a design capacity of CHP $a \in A$. Based on this generic superstructure, a mathematical model is formulated and shown in the following subsections.

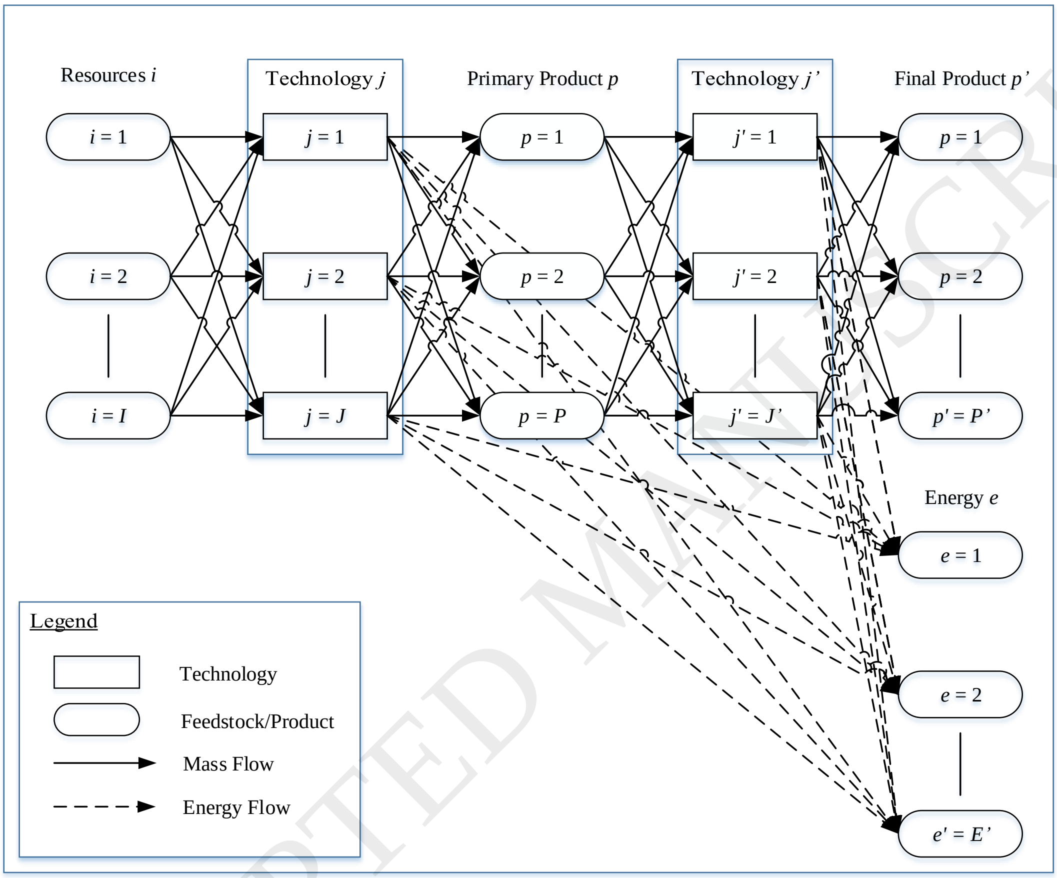

Fig. 2 General Superstructure Representation for Biomass CHP Design [35]

2.2 Mathematical Model Formulation

The mathematical model formulation includes mass and energy conversions, capital expenditure (CAPEX) and operating expenditure (OPEX) of equipment, gross profits, and decision analysis.

2.2.1 Mass and Energy Conversions

In this work, mass and conversion formulations for each technology are developed based on a given design capacity *a* and energy demand occurring in scenario *b*. F_i shown in Equation 1 represents the available mass flow for biomass *i*. Based on the available F_i, the biomass is distributed to potential technology *j*. This distribution of mass flow to technology *j* is represented by F_{ij} in Equation (1).

$$(F_i)_{ab} = (\sum_{j=1}^{J} F_{ij})_{ab} \qquad \forall a \forall b \forall i \qquad (1)$$

Equation (2) describes the conversion of F_{ij} into product *p* based on a fixed conversion factor of θ_{jp} at each technology *j*. Total mass flow rate of primary product *p* production in all technologies *j* is given as F_p.

$$(F_p)_{ab} = (\sum_{j=1}^{J} \sum_{i=1}^{I} \theta_{jp} F_{ij})_{ab} \qquad \forall a \forall b \forall p \qquad (2)$$

The primary product *p* is then split to technology *j'* for further conversion into final product *p'*. The distribution of primary product *p* to technology *j'* is as shown in Equation (3).

$$(F_p)_{ab} = (\sum_{j'=1}^{J'} F_{pj'})_{ab} \qquad \forall a \forall b \forall p \qquad (3)$$

Equation (4) shows the distributed mass flow of primary product (given by $F_{pj'}$) is converted into final product *p'* ($F_{p'}$) through technology *j'* based on fixed conversion factors of technology *j'* ($\theta_{j'p'}$).

$$(F_{p'})_{ab} = (\sum_{j'=1}^{J'} \sum_{p=1}^{P} \theta_{j'p'} F_{pj'})_{ab} \qquad \forall a \forall b \forall p' \qquad (4)$$

Apart from mass conversion, biomass *i* distributed into technologies *j* and *j'* can also be converted into energy *e* based on fixed energy conversion factor of n_{je} and $n_{j'e}$ respectively. The total energy produced from technologies *j* and *j'* is determined using Equation (5). Energy produced will be sold to satisfy energy demand E_e^{demand} with possibility of having excess energy E_e^{excess} as shown in Equation (6). E_e^{excess} is then fed back to palm oil mill as supporting energy supply or to neighbouring facilities.

$$(E_e^{\mathrm{T}})_{ab} = \left(\sum_{j=1}^{J}\sum_{i=1}^{I} \mathrm{n}_{je} F_{ij} + \sum_{j'=1}^{J'}\sum_{p=1}^{P} \mathrm{n}_{j'e} F_{pj'}\right)_{ab} \qquad \forall a \forall b \forall e \qquad (5)$$

$$(E_e^{\mathrm{T}})_{ab} = (E_e^{\text{demand}} + E_e^{\text{excess}})_{ab} \qquad \forall a \forall b \forall e \qquad (6)$$

2.2.2 Total Capital and Operating Cost

The total cost for a CHP system includes capital expenditure (*CAPEX*) and operating expenditure (*OPEX*) for each selected technology *j* and *j'*. Cost of technologies *j* and *j'* are given as C_j and $C_{j'}$ and determined via Equations (7) and (8). k_j^{CAPEX} and $\mathrm{k}_{j'}^{CAPEX}$ are *CAPEX* cost factor while k_j^{OPEX} and $\mathrm{k}_{j'}^{OPEX}$ are the *OPEX* cost factor of given per unit of mass flow rates F_{ij} and $F_{pj'}$ for technologies *j* and *j'* respectively [36]. CRF is the capital recovery factor and it is determined via Equation (9). In this work, CRF is used as a factor to annualise the *CAPEX* for uniform payment based on the operation lifespan, t and interest rate, r.

$$(C_j)_{ab} = \left(\sum_{i=1}^{I} \mathrm{k}_j^{CAPEX} F_{ij} \cdot \mathrm{CRF} + \sum_{i=1}^{I} \mathrm{k}_j^{OPEX} F_{ij}\right)_{ab} \qquad \forall a \forall b \forall j \qquad (7)$$

$$(C_{j'})_{ab} = \left(\sum_{p=1}^{P} \mathrm{k}_{j'}^{CAPEX} F_{pj'} \cdot \mathrm{CRF} + \sum_{p=1}^{P} \mathrm{k}_{j'}^{OPEX} F_{pj'}\right)_{ab} \qquad \forall a \forall b \forall j' \qquad (8)$$

$$\mathrm{CRF} = \frac{\mathrm{r}(1+\mathrm{r})^{\mathrm{t}}}{(1+\mathrm{r})^{\mathrm{t}} - 1} \tag{9}$$

The total cost (C^{Total}) which consists of *CAPEX* and *OPEX* of technologies *j* and *j'* is calculated using Equation (10).

$$(C^{\mathrm{Total}})_{ab} = \left(\sum_{j=1}^{J} C_j + \sum_{j'=1}^{J'} C_{j'} \right)_{ab} \qquad \forall a \forall b \tag{10}$$

2.3 Gross Profit

Based on the calculated $(C^{\mathrm{Total}})_{\mathrm{ab}}$ (Equation 10), gross profit of the designed CHP system can be determined by Equation (11). As shown, $(P^{\mathrm{Gross}})_{ab}$ is the gross profit of the CHP system and AOT is its annual operation time at designed capacity *a* and energy demand occurring in scenario *b*. $\mathrm{Tariff}_e^{\mathrm{demand}}$ is the FiT rates for each type of energy *e* generated by the biomass CHP system. FiT rates may vary depending on the location's local government policies. $\mathrm{Tariff}_e^{\mathrm{excess}}$ is the tariff rates charged on the excess energy supplied to the owner's POM or neighbouring facilities.

$$(P^{\mathrm{Gross}})_{ab} = \mathrm{AOT}\left(\sum_{e=1}^{E} (E_e^{\mathrm{demand}} \times \mathrm{Tariff}_e^{\mathrm{demand}} + E_e^{\mathrm{excess}} \times \mathrm{Tariff}_e^{\mathrm{excess}} \right)_{ab} - (C^{\mathrm{Total}})_{ab} \qquad \forall a \forall b \tag{11}$$

Based on the proposed model in Equations (1) – (11), the gross profit table can be constructed according to the general format, as shown in Table 1. Note that there a few key rules applied when computing the gross profits. Firstly, the gross profits in the shaded diagonal cells are computed by setting the objective as maximising Equation (12) as shown as below:

$$\text{Maximise } (P^{Gross})_{ab} \qquad \forall a \forall b \tag{12}$$

Table 1 General Table for Gross Profits

Design Capacity A	Occurring Energy Demand B					Lowest Gross Profit	Highest Gross Profit
	b* = *1	***b* = *2***	***b* = *3***	**…**	***b* = *B***		
a* = *1	P_{11}	P_{12}	P_{13}	…	P_{1B}	$P_1^{\min}$	$P_1^{\max}$
a* = *2	P_{21}	P_{22}	P_{23}	…	P_{2B}	$P_2^{\min}$	$P_2^{\max}$
a* = *3	P_{31}	P_{32}	P_{33}	…	P_{3B}	$P_3^{\min}$	$P_3^{\max}$
⋮	⋮	⋮	⋮		⋮	⋮	⋮
a* = *A	P_{A1}	P_{A2}	P_{A3}	…	P_{AB}	$P_A^{\min}$	$P_A^{\max}$

These shaded diagonal cells represent the profits obtained when the CHP system is designed at capacity which is equal to the occurring energy demand. Meanwhile, the remaining cells in Table 1 represent cases whereby the designed capacity of the CHP system (e.g., a = 1) is not equal (higher or lower) to energy demand occurring in a given scenario (e.g., b = 2). In this context, the gross profits of these cells are computed based on the following assumptions;

1. If the capacity of the designed CHP system is lower than the occurring energy demand, the gross profit would be the maximum attainable profit based on the given capacity. This is because the CHP can only produce the power based on the design capacity.
2. If the capacity of the CHP system is higher than the occurring energy demand, the maximum gross profit would be based on the given occurring energy demand. This is because the profit can only generate based on the energy sold to meet the energy demand.

Based on the gross profit table, the following step in the proposed framework is dependent on the type of decision to be made as described in the next section.

2.4 Decision Analysis

As mentioned previously, the proposed framework considers three types of decisions; Maximax Criterion, Maximin Criterion and Minimax Regret Criterion. These types of decision are explained in the following sub-sections.

2.4.1 Maximax Criterion

Maximax criterion is used when the decision-maker intends to make an optimistic decision. This type of decision-maker seeks to achieve the best results assuming that the best scenario will happen no matter what action is taken. In Maximax Criterion, the highest gross profit of each alternative biomass CHP design are computed in a general format in the last column on the right of Table 1. This is achieved by determining the highest gross profit value for each row in Table 1 as shown in Equation (13).

$$\begin{aligned}
P_1^{\max} &= \max\{P_{11}, P_{12}, P_{13}, \ldots, P_{1B}\} \\
P_2^{\max} &= \max\{P_{21}, P_{22}, P_{23}, \ldots, P_{2B}\} \\
P_3^{\max} &= \max\{P_{31}, P_{32}, P_{33}, \ldots, P_{3B}\} \\
&\vdots \\
P_A^{\max} &= \max\{P_{A1}, P_{A2}, P_{A3}, \ldots, P_{AB}\}
\end{aligned} \tag{13}$$

Following this, the CHP design with the highest value among $P_1^{\max}$, $P_2^{\max}$, $P_3^{\max}$ …, $P_A^{\max}$ is selected. This decision represents the optimistic decision-maker is determined as shown in Equation (14);

$$(P_A^{\max})^{\max} = \max\{P_1^{\max}, P_2^{\max}, P_3^{\max}, ..., P_A^{\max}\} \tag{14}$$

2.4.2 Maximin Criterion

Maximin criterion is used when a pessimistic decision must be made. Unlike Maximax criterion, Maximin favours the alternative design considering the worst possible outcome, with the best results. In this respect, the lowest gross profit of each row in Table 1 is determined via Equation (15) and computed in a general format as shown in the second column from the right.

$$\begin{aligned} P_1^{\min} &= \min\{P_{11}, P_{12}, P_{13}, ..., P_{1B}\} \\ P_2^{\min} &= \min\{P_{21}, P_{22}, P_{23}, ..., P_{2B}\} \\ P_3^{\min} &= \min\{P_{31}, P_{32}, P_{33}, ..., P_{3B}\} \\ &\vdots \\ P_A^{\min} &= \min\{P_{A1}, P_{A2}, P_{A3}, ..., P_{AB}\} \end{aligned} \tag{15}$$

Subsequently, the Maximin criterion selects a CHP design with the highest value among $P_1^{\min}$, $P_2^{\min}$, $P_3^{\min}$ …, $P_A^{\min}$ as shown in Equation (16);

$$(P_A^{\min})^{\max} = \max\{P_1^{\min}, P_2^{\min}, P_3^{\min}, ..., P_A^{\min}\} \tag{16}$$

2.4.3 Minimax Regret Criterion (MRC)

MRC is used when the decision-maker is aiming to make a risk-neutral decision. Business and financial models commonly employ MRC approach to make a decision that with least regret [29, 32]. The term "regret" refers to the difference between actual gross profit obtained and the potential gross profit that could have been obtained if it was not for making a wrong decision in design [29, 32]. For instance, if the biomass CHP system is designed for a higher capacity, but the actual occurring energy demand in real time is lower, this would be considered a wrong design decision. As a result, the designed biomass CHP would generate gross profits lower than the gross profit that should have been obtained if the actual occurring energy demand was equal to the higher capacity (as indicated in Table 1). The difference between actual gross profit obtained and the potential gross profit is taken as the regret (as shown in Table 2). Once the regret table is computed, the highest regret values for each row in Table 2 is determined. The highest regret value for each row is computed (i.e., R_1^{max}, R_2^{max},…, R_A^{max}) using Equation (17). This is shown in the column on the far right of Table 2.

$$
\begin{aligned}
R_1^{max} &= \max\{R_{11}, R_{12}, R_{13}, ..., R_{1B}\} \\
R_2^{max} &= \max\{R_{21}, R_{22}, R_{23}, ..., R_{2B}\} \\
R_3^{max} &= \max\{R_{31}, R_{32}, R_{33}, ..., R_{3B}\} \\
&\vdots \\
R_A^{max} &= \max\{R_{A1}, R_{A2}, R_{A3}, ..., R_{AB}\}
\end{aligned} \tag{17}
$$

Based on the highest regret values computed in the column on the far right of Table 2, the design with lowest regret value is chosen (Equation (18)). This chosen CHP design indicates the design with the lowest loss of potential profit.

$$
(R_A^{max})^{min} = \min\{R_1^{max}, R_2^{max}, R_3^{max}, ..., R_A^{max}\} \tag{18}
$$

Table 2 General Table for Regret

Design Capacity A	Occurring Energy Demand B					Maximum Regret Value
	***b* = 1**	***b* = 2**	***b* = 3**	**…**	***b* = B**	
***a* = 1**	$R_{11} = \lvert P_{11} - P_{11}\rvert$	$R_{12} = \lvert P_{12} - P_{22}\rvert$	$R_{13} = \lvert P_{13} - P_{33}\rvert$	…	$R_{1B} = \lvert P_{1B} - P_{AB}\rvert$	R_1^{max}
***a* = 2**	$R_{21} = \lvert P_{21} - P_{11}\rvert$	$R_{22} = \lvert P_{22} - P_{22}\rvert$	$R_{23} = \lvert P_{23} - P_{33}\rvert$	…	$R_{2B} = \lvert P_{2B} - P_{AB}\rvert$	R_2^{max}
***a* = 3**	$R_{31} = \lvert P_{31} - P_{11}\rvert$	$R_{32} = \lvert P_{32} - P_{22}\rvert$	$R_{33} = \lvert P_{33} - P_{33}\rvert$	…	$R_{3B} = \lvert P_{3B} - P_{AB}\rvert$	R_3^{max}
⋮	⋮	⋮	⋮		⋮	⋮
***a* = A**	$R_{A1} = \lvert P_{A1} - P_{11}\rvert$	$R_{A2} = \lvert P_{A2} - P_{22}\rvert$	$R_{A3} = \lvert P_{A3} - P_{33}\rvert$	…	$R_{AB} = \lvert P_{AB} - P_{AB}\rvert$	R_A^{max}

In the next section, Maximax criterion, Maximin criterion and MRC are demonstrated using an illustrative example. Next, the demonstration is extended further to a more detailed palm-based biomass CHP case study. Following this, sensitivity analysis was conducted on FiT rates to analyse change of FiT rates and its corresponding impact on the biomass CHP design. Lastly, the biomass CHP design is analysed further to determine which equipment that are commonly selected and avoided.

3. Illustrative Example

To understand the proposed framework in Figure 1, Maximax criterion, Maximin criterion and MRC are first demonstrated using a simplified illustrative example. In this illustrative example, it is assumed that a CHP system must be designed to meet three energy demands *b* that may occur; 60, 70 and 80 kW/day. To meet these possible energy demands, three alternatives with design capacities of *a* = 60, 70 and 80 kW/day are considered.

Table 3 shows the generated gross profits for this example. The first row indicates the case when the CHP is designed at 60 kW/day (i.e., a = 1) capacity. If 60 kW/day energy demand occurs (i.e., b = 1), the expected gross profit is 130 RM/day. However, if the energy demand b occurs at 70 or 80 kW/day (i.e., b = 2, 3), the CHP system with capacity of 60 kW/day (i.e., a = 1) is only able to generate gross profit of 130 RM/day. This is because the CHP is unable to generate more power as that would exceed its designed capacity. Meanwhile, the second row refers to the CHP design with capacity of 70 kW/day (i.e., a = 2). When 70 kW/day energy demand occurs (i.e., b = 2), the expected gross profit is 200 RM/day. Similarly, if the occurring energy demand is 80 kW/day (i.e., b = 3), the corresponding gross profits would be same as 200 RM/day as the designed capacity at 70 kW/day (i.e., a = 2) unable to generate more power exceeding its capacity. However, if opposite occurs, whereby the energy demand occurring is lower than 70 kW/day, the profit obtained will be lower than 200 RM/day. This is due to higher capital and operational cost for larger capacity CHP design. Based on the gross profits shown in Table 3, Maximax and Maximin Criterion can be demonstrated using Equations (13 – 16) to determine optimistic and pessimistic decisions respectively.

Table 3 Gross Profit Table for Illustrative Example (RM/day)

Design Capacity	**Occurring Energy Demand (kW/day)**			**Lowest Gross Profit**	**Highest Gross Profit**
(kW/day)	**60**	**70**	**80**		
60	130	130	130	130	130
70	100	200	200	100	200
80	70	170	270	70	270

For Maximax criterion, the highest gross profit attainable for each design capacity (or each row) is computed using Equation (13), as shown in the far right column of Table 3. The highest gross profits for each row are 130, 200 and 270 RM/day respectively. Based on these gross profits, the Maximax criterion suggests choosing the design capacity with largest gross profit value (Equation (14)). As a result, the CHP system with design capacity of 80 kW/day (i.e., a = 3) is chosen as it has the largest maximum gross profit value. Note that this represents the decision of an optimistic decision-maker.

Alternatively, Maximin criterion requires the lowest attainable gross profits to be computed. The lowest gross profits attainable for each design capacity are computed using Equation (15) in the second column from the right in Table 3. From here, the largest value among the gross profits is chosen using Equation (16), i.e., the CHP system with design capacity of 60 kW/day (i.e., a = 1). Hence, the CHP system with design capacity of 60 kW/day (i.e., a = 1) represents the pessimistic decision.

As for MRC, a regret table is generated based on the profit table (Table 3). Table 4 shows the regret table for this illustrative example. As shown in shaded diagonal cells of Table 4, when design capacity is equal to energy demand, no regret is computed since the CHP design capacity meets the exact energy demand occurred. As mentioned previously, the term "regret" is the difference between actual gross profit obtained and the potential gross profit that could have been obtained. Meanwhile, if the design capacity does not meet the energy demand occurred, a corresponding regret is computed as shown in Table 2. To illustrate this clearly, the first row of the regret table is examined. The first row refers to the CHP system with design capacity of 60 kW/day (i.e., a = 1). When the occurring energy demand is 70 kW/day (i.e., b = 2), a regret value of 200 – 130 = 70 RM/day will be obtained. This shows that an excess of 70 RM/day could have been earned if the CHP system was designed at 70 kW/day (i.e., a = 2) instead of 60 kW/day (i.e., a = 1). Using similar reasoning, the remaining regret values are computed using generic regret table (Table 2). Based on the computed regret values in Table 4, the highest regret for each design (or row) are computed as 140, 70 and 60 RM/day respectively using Equation (17). Following this, MRC is used to choose the design capacity with the lowest regret value using Equation (18). As such, the CHP design with design capacity of 80 kW/day (i.e., a = 3) is chosen if a risk-neutral decision is required.

Table 4 Regret Table for Illustrative Example (RM/day)

Design Capacity (kW/day)	Occurring Energy Demand (kW/day)			Highest Regret Value
	60	70	80	
60	0	70	140	140
70	30	0	70	70
80	60	30	0	60

Based on the results obtained in this illustrative example, it can be observed that the chosen CHP system design capacity varies based on the type of decision-maker. The following section provides a detailed demonstration of the proposed framework.

4. Case Study

Malaysia is one of the large producers of lignocellulosic biomass. In fact, approximately 82.61 wt% of total biomass in Malaysia is produced in palm oil industry and plantations[38]. Palm-based biomass are by-products produced from palm oil mill during the extraction process of crude palm oil (CPO) from fresh fruit bunches. Palm-based biomass includes solid biomass such as palm mesocarp fibre (PMF), empty fruit bunches (EFB), palm kernel shell (PKS) and wastewater i.e., palm oil mill effluent (POME). Besides, oil palm frond and trunk are also generated in the plantations. According to the Malaysian Palm Oil Board (MPOB) [4], the total amount of EFB, PMF and PKS was estimated to be about 29.69 million tonnes. Meanwhile, 41.83 million tonnes POME was estimated to be generated in Malaysia at 2017. [4,39]. By wet weight, the weight composition of the solid palm-based biomass is shown in Table 5 [39,40]. EFB, PMF, PKS and POME possess high calorific value which can be utilised in biomass combined heat and power (CHP) systems to produce useful heat and power [41]. The calorific values of these palm-based biomass is shown in Table 6 [38]. Based on the high calorific values, recovering energy from palm-based biomass can provide high amount of energy.

Table 5 Weight composition of Solid Palm-based Biomass in Malaysia [39,40]

Component	**Composition (wt%)**	**Weight (million tonnes)**
EFB	54	15.35
PMF	30	8.52
PKS	16	4.55
Total	100	28.42

Table 6 Calorific value of Palm-based biomass [38]

Palm-based Biomass Component	**Calorific Value (kJ/kg)**	**Moisture Content (%)**
EFB	6,028	57.2
PMF	19,068	37.2
PKS	18,836	21.4
POME	22	100

In 2001, the Malaysian government launched the Small Renewable Energy Power (SREP) program to boost industrial involvement in utilising agricultural wastes to generate power for the national grid. At the present time, most palm oil mills in Malaysia have installed biomass CHP systems to satisfy internal energy demands but almost none are connected to the national grid. Surveys conducted by Umar et al. [37,42,43] suggested that this is due to reasons such as uncertainty in seasonal biomass supply to meet varying energy demands, unattractive governmental schemes for grid connection and the risk of investing in capital cost intensive biomass CHP projects. As such, this case study applies the approach presented in Figure 1 to design an optimal biomass CHP system for power demands of 5, 7, 10 and 15 MW via the cautious or risk-neutral approach. In short, the CHP design would be determined based on potential "regret".

Figure 3 shows the superstructure developed for this palm-based biomass CHP case study. In this case study, biomass resources *i* refers to solid palm-based biomass and POME with notation of F_o and F_{POME} respectively in Figure 3. Technology *j* converts the biomass (F_o or F_{POME}) into intermediate products *p* and subsequently convert into power through another layer of technologies *j'*. Note that for the purpose of illustration, this case study considers only three pathways. In the case where the decision maker would like to consider more options of technologies, the proposed framework is adaptable to include more technology pathways. The level of detail and the number of equipment considered in the superstructure is highly dependent on the decision-maker and available information. In this case study, three technology pathways are considered:

Pathway 1: Solid palm-based biomass undergo pre-treatment with shredder which reduces the size of biomass to a common feed size specification of 2 inches diameter for boilers. Then, dryer is used to reduce the moisture content of biomass to less than 30% which is a common specification for biomass combustion in water tube boilers. The treated biomass is subsequently combusted in two possible types of water tube boilers to produce saturated steam of 18 bar. Correlation for the amount of steam produced per unit treated biomass is obtained from Environmental Protection Agency CHP catalogue [46]. The steam produced is then flowed into a steam turbine to generate power.

Pathway 2: In this pathway, solid palm-based biomass undergoes similar pre-treatment with a shredder. The shredded biomass is then dried to a moisture content less than 20% for the gasification unit. The treated biomass is subsequently converted into syngas through gasification. Correlation for amount of syngas produced per unit treated biomass is taken from Environmental Protection Agency CHP catalogue [46]. Syngas produced is inserted into power generation technology such as gas engine, gas turbine and micro-turbine to generate power.

Pathway 3: POME undergo anaerobic digestion in a digester to produce raw biogas with. The composition of raw biogas produced is 65wt% of methane and 35wt% of carbon dioxide. Raw biogas is then treated using an amine scrubber with carbon dioxide removal rate of 99.8wt%. Correlation for the amount of methane removed per unit POME volumetric flow rate is obtained through data collected from industrial networks[47]. Purified biogas is then passed into power generation technology such as gas engine, gas turbine and micro-turbine to generate power.

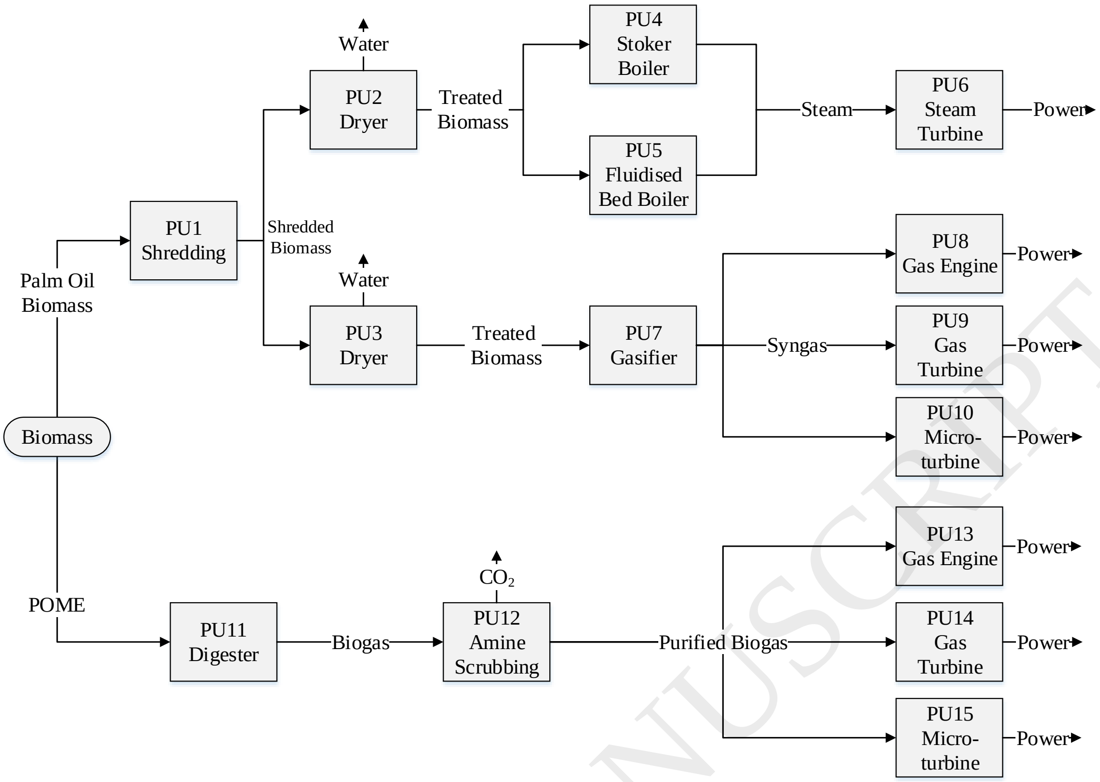

Fig. 3 Biomass CHP Superstructure

Note that the proposed approach is adaptable to any type of energy demands specified in the case study. The case study in this work particularly focuses on showing the screening of various pathways to meet power demands and selection of a suitable one. So the three pathways considered in the case study are pathways that eventually produce power. If it is in the interest of the decision-maker to meet heat demands as well, then technologies that utilise residual heat from the gas engines or other equipment can be added as the approach is adaptable. Hence, the level of detail in the superstructure would depend on the purview of the decision-maker.

A mixed integer linear programming (MILP) model is then formulated using procedures shown in Section 2 to describe the biomass CHP superstructure developed. Aside from this, the following assumptions are used in the model;

1. The available supply of biomass is 15,000 kg/hr solid palm-based biomass mixture and 15 m^3/day of and POME.
2. AOT of the biomass CHP plant is taken as 8,000 hours of annual operating time.
3. Average FiT rates used for biomass power and biogas power generation are RM 0.2985/kWh and RM 0.2886/kWh respectively [44].
4. Capital expenditure (*CAPEX*) is paid in uniform payment annually for 15 years with interest rate of 10% annually. Thus, capital recovery factor (CRF) is 0.1315/year.
5. In this case study, biomass feedstock is generated as waste materials in a palm oil mill and is supplied to the CHP system at no cost. Hence, there is no cost incurred on biomass feedstock used by the CHP system.

Based on the assumptions stated above, the MILP model developed is solved via a commercial optimisation software, LINGO version 17 with global solver. The MILP model consists of 75 variables, 15 integers and 70 constraints. It was solved under 3 seconds for each computation on the gross profit table using HP Compaq Elite 8300 with a 32-bit operating system, Intel® Core™ i5-3470 CPU (3.20GHz) processor and 4.00 GB RAM.

The corresponding cost for each equipment in each biomass CHP design is shown in Table 7. Note that the cost for each equipment refers to the calculated CAPEX. If the decision-maker intends to conduct a more rigorous evaluation, other cost factors such as maintenance cost and operation cost can be included in the adaptable framework proposed. Equipment that are not selected in the CHP design at its respective designed capacity will have their cost value shown as zero. The biomass CHP design determined at its respective designed capacity while gross profit are maximised and the corresponding revenue and total cost are shown in Table 8.

At designed capacity of 5 MW (i.e., a = 1), only process unit PU_{11}, PU_{12} and PU_{13} have cost values as shown in Table 7. Hence, the equipment involved in biomass CHP design for 5 MW are biogas generation with gas engine as shown in Figure 4. Similarly, for designed capacity of a = 7, 10 and 15 MW (i.e., a = 2, 3 and 4), the equipment involved in the biomass CHP design which provide maximum gross profit at each specific energy demand are shown in Figures 5, 6 and 7 respectively. Meanwhile, the gross profit for each biomass CHP designs are tabulated in Table 9.

Table 7 Cost of each Equipment respective to Designed Capacity (RM)

Equipment No.	Designed Capacity (MW)			
	5	7	10	15
PU1	0	3,716,397	29,279,280	38,190,000
PU2	0	0	895,508	1,165,000
PU3	0	122,397	0	0
PU4	0	0	42,807,160	53,238,390
PU5	0	0	0	0
PU6	0	0	9,923,000	13,085,970
PU7	0	7,246,465	0	0
PU8	0	1,686,391	0	0
PU9	0	0	0	0
PU10	0	0	0	0
PU11	34,817	41,980	0	17,565
PU12	18,925,090	24,387,490	0	5,769,177

PU13	11,950,100	15,283,810	0	3,921,034
PU14	0	0	0	0
PU15	0	0	0	0
Total Cost	30,910,007	52,484,930	82,908,948	115,387,136

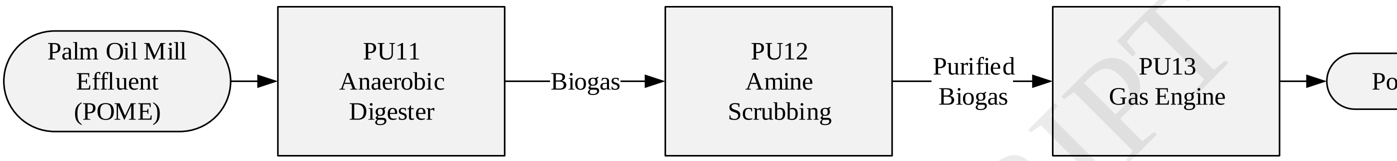

Fig. 4 Optimum Design for 5 MW Power Demand

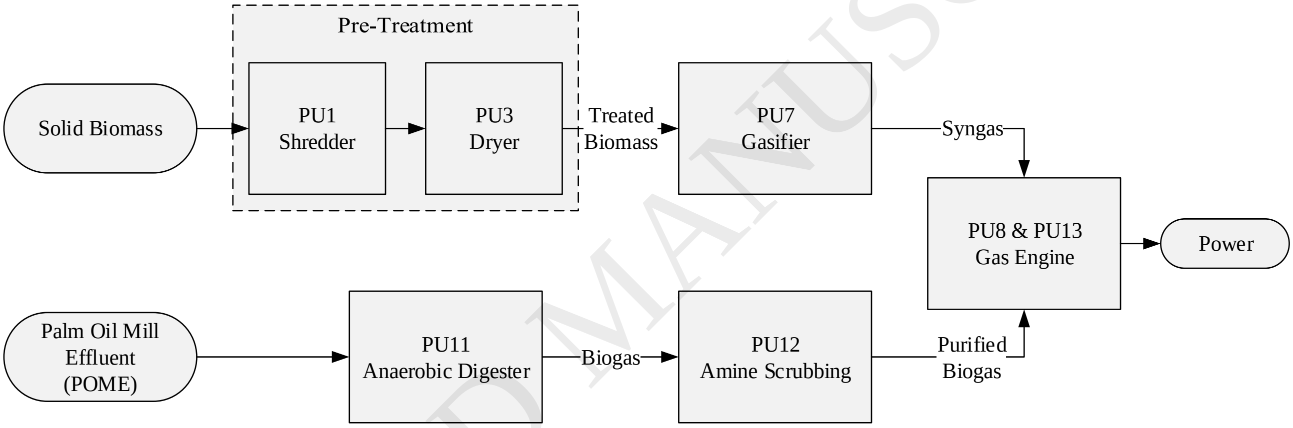

Fig. 5 Optimum Design for 7 MW Power Demand

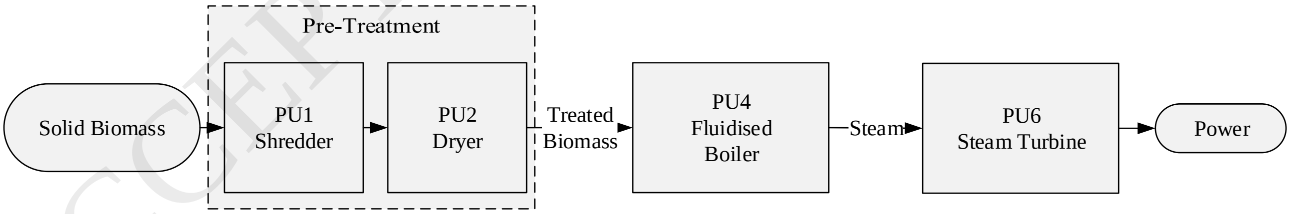

Fig. 6 Optimum Design for 10 MW Power Demand

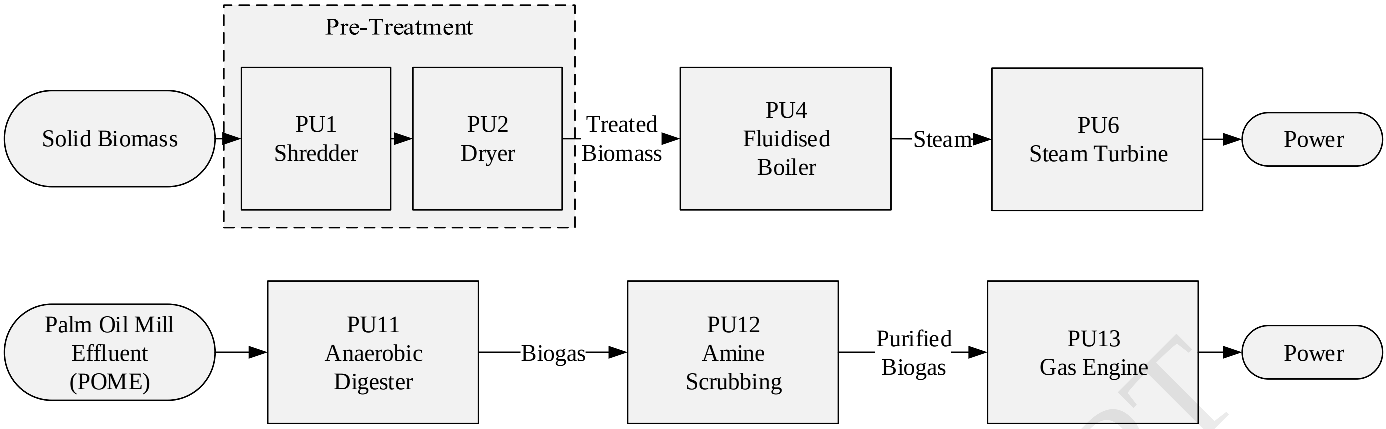

Fig. 7 Optimum Design for 15 MW Power Demand

Table 8 Revenue and Total Cost of each Biomass CHP Design

Design	**Design Capacity (MW)**	**Revenue (RM/year)**	**Total Cost (RM/year)**
Biogas with GE (Fig. 4)	5	11,560,000	4,080,121
Syngas + Biogas GE (Fig.5)	7	16,228,550	6,928,010
Boiler + Steam Turbine (Fig. 6)	10	23,920,000	10,943,453
Boiler + Steam Turbine and Biogas with GE (Fig. 7)	15	35,758,060	15,231,101

As indicated in Table 9, values found in parentheses represent negative gross profit or loss. The gross profit computed in the shaded diagonal cells is the result of the difference between revenue obtained from a given power demand and total cost of its respective designed capacity. This is shown in the calculation below, taken from Table 8. As shown, the total cost of the biogas powered gas engine system at capacity of 5 MW (i.e., $a = 1$) is 4,080,121 RM/year while the revenue obtained using this system is 11,560,000 RM/year at occurring power demand of 5 MW (i.e., $b = 1$). The difference between these two values denotes the gross profit using Equation (11).

$(P^{Gross})_{11}$ = 11,560,000 RM/year - 4,080,121 RM/year = 7,479,879 RM/year

Table 9 Computed Gross Profit Table for Case Study in terms of RM/year

Designed Capacity (MW)	**Occurring Power Demand (MW)**			
	5	**7**	**10**	**15**
5	7,479,879	7,479,879	7,479,879	7,479,879
7	4,631,990	9,300,536	9,300,536	9,300,536
10	616,547	5,285,097	12,976,550	12,976,550
15	(3,671,101)	997,449	8,688,899	20,526,960

*Values in parentheses represents negative profit of the designed capacity

When the biomass CHP system is designed at a capacity lower than the occurring power demand, the gross profit obtained is limited by the designed capacity. This is because the biomass CHP design had reached its maximum capacity, hence it can only meet power demands within its capacity and not beyond. For example, when the CHP system is designed at capacity of 5 MW (i.e., a = 1) and the occurring power demand is 7 MW (i.e., b = 2), the system will only be able generate a maximum of 5 MW. Hence, the gross profit for this case would be 7,479,879 RM/year which is equivalent to gross profit when occurring power demand b is 5 MW (i.e., b = 1). On the other hand, if the occurring power demand is lower than the designed capacity, the gross profit obtained by the biomass CHP system is lower as the system is not operating at full capacity. For instance, when the CHP system is designed at capacity of 7 MW (i.e., a = 2) and the occurring power demand 5 MW (i.e., b = 1), the system will only generates 5 MW worth of revenue. However, the total cost incurred here would be for a 7 MW capacity CHP design (i.e., a = 1). In this respect, the gross profit of this situation was determined as:

$(P^{Gross})_{21}$= 11,560,000 RM/year - 6,928,010 RM/year = 4,631,990 RM/year

Gross profit for other combinations of power demand and designed capacity of the biomass CHP system will follow similar reasoning as shown above.

Next, a regret table was developed based on the gross profit table shown in Table 9. In the regret table, the maximum regret for each biomass CHP design is computed. As "regret" refers to loss of profit due to a wrong design decision, there will be no regret value when the CHP design capacity meets the occurring power demand. This explains the reason as to why shaded regret values from top left to bottom right corner appears to have no value. In the case where the designed capacity is lower than the occurring power demand, there will be a regret value resulting from the lack of system capacity to fulfil the occurring power demand. The regret value for this situation was calculated through the difference between the gross profit that should have been obtained when the design capacity is equal to the occurring power demand and the gross profit that is actually obtained. For example, consider the case when the biomass CHP system is designed at 5 MW (i.e., a = 1) and the occurring power demand is 7 MW (i.e., b = 2). The gross profit that should have been obtained is 9,300,536 RM/year if the system was designed at 7 MW (i.e., a = 2). Unfortunately, the actual gross profit obtained is 7,479,879 RM/year for only able to feed in 5 MW (shown in Table 9). Therefore, this situation gives a quantifiable regret value of;

$R_{a=5,\, b=7}$ = 9,300,536 RM/year – 7,479,879 RM/year = 1,820,657 RM/year

Similarly, the reasoning above is used in situations where the designed capacity of the CHP system is lower than the occurring power demand. In this case, there is a regret value for overdesigning the biomass CHP system. Summary of the regret values obtained in this case study is shown in Table 10.

Table 10 Computed Regret Table for Case Study in terms of RM/year

Designed Capacity (MW)	Occurring Power Demand (MW)				Highest Regret Value
	5	**7**	**10**	**15**	
5	-	1,820,657	5,496,671	13,047,081	13,047,081
7	2,847,889	-	3,676,014	11,226,424	11,226,424
10	6,863,332	4,015,439	-	7,550,410	7,550,410
15	11,150,980	8,303,087	4,287,651	-	11,150,980

The maximum regret value of each biomass CHP design capacity was identified as shown in Table 10 (see each row). Based on Minimax Regret Criterion (MRC) approach, the biomass CHP design with the smallest maximum regret value will provide the least possible loss of profit with the gross profit of the system maximised. Based on regret values shown in Table 10, the design capacity with the lowest maximum regret value is 10 MW biomass CHP design (i.e., 7,550,410 RM/year). The biomass CHP design at 10 MW (i.e., a = 3) consists of the boiler with steam turbine power generation pathway and it provides lowest maximum regret.

4.1 Sensitivity Analysis

In Malaysia, various FiT rates are offered depending on whether power was generated using biogas or solid biomass. Aside from this, FiT rates may differ based on installed capacity.

As such, a sensitivity analysis on the FiT rate is performed in this section. In the previous section, the FiT rates used were 0.2985 RM/kWh and 0.2886 RM/kWh for biomass power and biogas power generation respectively[44]. In this sensitivity analysis, the previous FiT rates were varied according to the percentages shown in Table 11. From Table 11, the effect of FiT rate variation on the optimal CHP design is evident. According to Table 11, it is found that at lower FiT rates, GE and syngas generation were selected as the optimal CHP design. This means that GE and syngas generation are more suitable when FiT rates experience a drop. On the other hand, it is noted that the boiler and steam turbine configuration was chosen as the optimal CHP design at higher FiT rates. Note that a change in selection of the optimal CHP design occurs when the FiT rate is 30% lesser than 0.2985 RM/kWh and 0.2886 RM/kWh for biomass and biogas power generation respectively.

Table 11 Results of Sensitivity Analysis

FiT Rates (%)	Optimum Design	Minimax Regret Value (RM/year)
-50	Biogas GE	5,613,212
-30	Syngas + Biogas GE	7,858,497
-10	Boiler with Steam Turbine	7,271,344
0	Boiler with Steam Turbine	7,550,410
10	Boiler with Steam Turbine	8,305,451
30	Boiler with Steam Turbine	9,815,533
50	Boiler with Steam Turbine + Biogas with GE	9,110,920

4.2 Further Analysis of Design

The optimal biomass CHP design is investigated further to analyse the trend of equipment selected within a range of power demand. This analysis allows identification of equipment that are mandatory across a given range of energy demand. “must-have” equipment are the compulsory equipment that must be included in the biomass CHP design. If decision-makers are ambitious and would like to aim for higher power demands, there are some “optional” equipment identified. Equipment that were not chosen for the power demand range investigated would be considered as “must-avoid" equipment. In addition, Figure 8 below illustrates the concept of “must-have”, “optional” and “must-avoid” equipment [45]. This analysis provides decision-makers insight on the selection of equipment and subsequently determine the biomass CHP design.

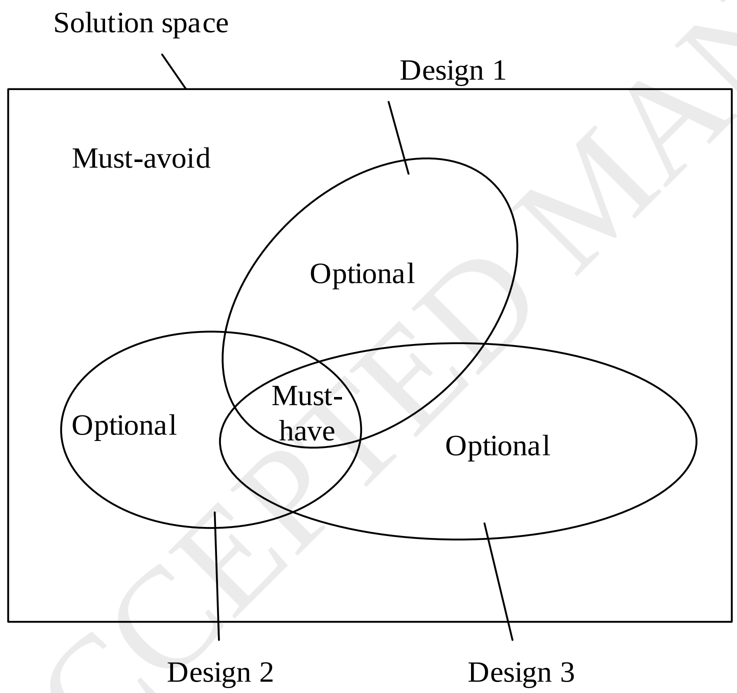

Fig. 8 Illustration of “must-have”, “optional” and “must-avoid” Concept adapted from Voll et. al [45]

The range of power demand analysed in this case study is from 1 MW to 15 MW. Table 12 shows the obtained results and CHP design determined using MRC approach for each power demand. Based on Table 12, there are common or "must-have" equipment selected for the range of power demands analysed. This is also shown in Figure 9. As shown, the "must-have" for power outputs up to 8 MW is biogas generation with GE. The "optional" equipment within this range is found to be the syngas generation. Meanwhile, for the range of 9 to 15 MW, the "must-have" equipment for the CHP system is boiler with steam turbine. The "optional" for this range would be the biogas with GE. It is found that the gas turbine and micro-turbine are the "must-avoid" equipment.

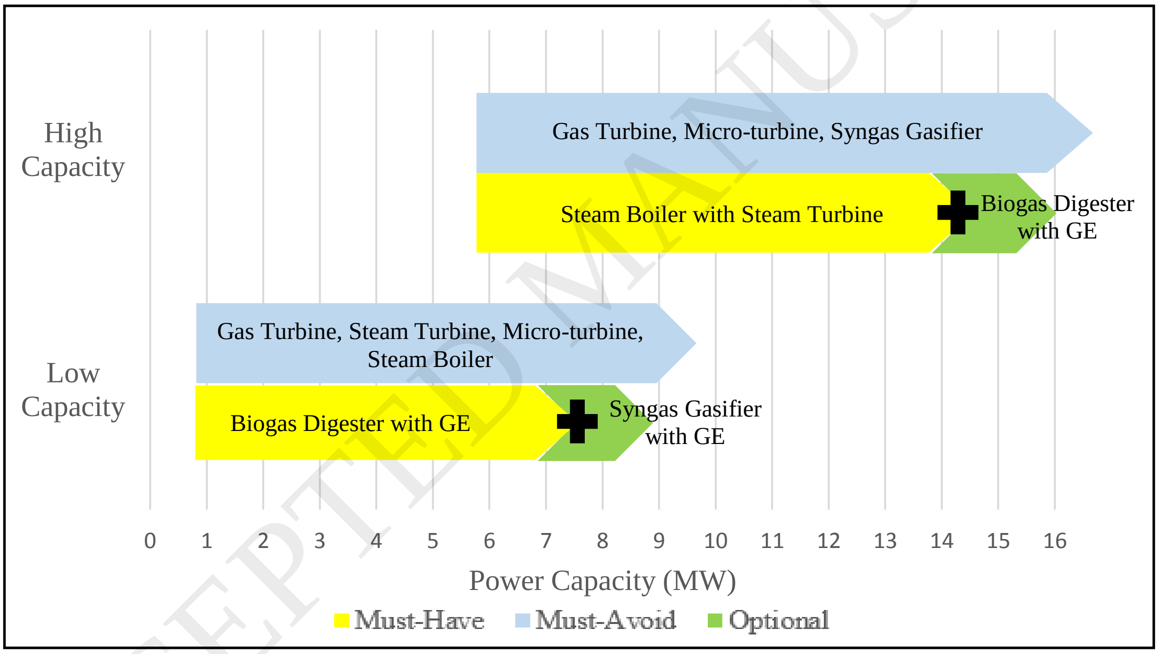

Fig. 9 Analysis of "Must-have", "optional" and "must-avoid" Design

Table 12 Further Analysis on Biomass CHP Design

Power Demand (MW)	**POME Utilised (m^3/day)**	**Solid Feed Utilised (kg/hr)**	**CHP Design**

1	2.33	0.00	Biogas with GE
2	4.66	0.00	
3	6.98	0.00	
4	9.31	0.00	
5	11.64	0.00	
6	13.97	0.00	
7	15.00	1,459.70	Combined Syngas and Biogas with GE
8	15.00	3,025.50	
9	0.00	10,493.17	Boiler with Steam Turbine
10	0.00	11,500.11	
11	0.00	12,507.04	
12	0.00	13,513.98	
13	0.00	14,520.91	
14	15.00	9,040.00	Combined Boiler with Steam Turbine and Biogas with GE
15	15.00	10,046.94	

On the other hand, Table 12 shows several key findings. For instance, the model had selected anaerobic digestion with GE to operate in low power demands ranging from 1 to 6 MW. Since the model is focused on maximising gross profit, the model did not favour utilisation of EFB, PKS and PMF due to the high capital cost required for pre-treatment equipment. When power demand rises to 7 to 8 MW, the model is found to have selected the combination of syngas generation and anaerobic digestion route. This is because the available amount of POME supply has been fully utilised at this point, hence needing additional make-up from another source, i.e., syngas generation. At much higher power demands, i.e., 9 to 13 MW, the model favours the selection of boilers. In this case, solid biomass is consumed in boilers to produce steam and subsequently to generate power via steam turbines. Note that syngas and biogas was not used for this range as there was insufficient supply. Thus, it is not economically viable to select biogas and syngas generation for high power demand range. As solid biomass is fully utilised for power demands above 13 MW, POME is utilised to make up for the remaining power demand. In addition, it is necessary note that only GE was chosen to utilise biogas and syngas to generate power instead of micro-turbine and gas turbine. In a nutshell, the analysis of biomass CHP design noted several key points;

1. For low range power demands, anaerobic digestion and gas GE are chosen.
2. For medium range power demands, the combination of syngas and biogas generation is preferred.
3. For high range power demands, boilers and steam turbines are chosen.
4. The commonly selected or "must-have" equipment to meet low range power demands is the anaerobic digester and GE. Syngas generation was found to be an "optional" equipment.
5. In high range power demands, boilers and steam turbines are the "must-have" equipment. "Optional" here includes anaerobic digestion and biogas utilisation in gas engine.

5. Conclusion

In this work, a decision analysis framework was presented for design of biomass CHP system based on the type of decision-maker. The proposed framework provided a stage-wise mathematical optimisation procedure which considered three types of decision-makers, using Maximax Criterion, Maximin Criterion and Minimax Regret Criterion (MRC). The proposed framework was demonstrated using a simple illustrative example. Following this, the framework was applied to a detailed palm-based biomass CHP case study. Moreover, a sensitivity analysis was performed in the case study to evaluate the effect of FiT rates on the optimum CHP design. The biomass CHP design was then analysed further within a range of power demand. In this analysis, the selected equipment were classified under the “must-have”, “optional” and “must-avoid” categories. It is important to note that the proposed framework can be further extended in future work to other aspects which include biomass supply variation, tariff rate variation, changes in government schemes, etc.

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