CHEMICAL ENGINEERING TRANSACTIONS
VOL. 89, 2021
A publication of AIDIC
The Italian Association of Chemical Engineering
Online at www.cetjournal.it
Guest Editors: Jeng Shiun Lim, Nor Alafiza Yunus, Jiří Jaromír Klemeš

ISBN 978-88-95608-87-7; **ISSN** 2283-9216
DOI: 10.3303/CET2189087

Optimal Biomass Cogeneration Facilities Considering Operation and Maintenance

Roziah Zailan[a,c], Jeng Shiun Lim[a,*], Siti Fatimah Sa'ad[b], Khairulnadzmi Jamaluddin[b], Abdulhalim Abdulrazik[d]

[a] Process Systems Engineering Centre (PROSPECT), Research Institute for Sustainable Environment (RISE), School of Chemical and Energy Engineering, Faculty of Engineering, Universiti Teknologi Malaysia, 81310 Johor Bahru, Johor, Malaysia
[b] School of Chemical and Energy Engineering, Faculty of Engineering, Universiti Teknologi Malaysia, 81310 UTM Johor Bahru, Johor, Malaysia
[c] Faculty of Civil Engineering Technology, College of Engineering Technology, Universiti Malaysia Pahang, Gambang Campus, 26300 Kuantan, Pahang, Malaysia
[d] Faculty of Chemical Engineering Technology, College of Engineering Technology, Universiti Malaysia Pahang, Gambang Campus, 26300 Kuantan, Pahang, Malaysia
jslim@utm.my

A development of biomass cogeneration facilities business comes with many challenges such as operational compliance and budget constraints. Maintenance cost is often oppressing some portion of the annual budget. Apparent outage costs due to loss of production during planned operation and maintenance are crucial. It requires a strategic maintenance framework to ensure optimum performance of the biomass cogeneration business. This paper presents a Mix Integer Linear Programming optimization model for the palm oil mill-based cogeneration facility considering fuel cost, electricity cost, maintenance duration and maintenance interval. The model aims to minimize total annual operation costs to ensure tenants can depend on reliable, uninterrupted heat as they deserved from the heat supplier. The sensitivity analysis results determine the lowest annualised cost had impacted by lower fuel and outsource electricity costs, six days maintenance duration, and 1.1 maintenance intervals.

1. Introduction

At present, biomass cogeneration facilities (BCF) have been increasingly accepted by industries as primary energy sources since oil, natural gas, and coal were expected to be depleted in the next 40 to 50 y (Abbas et al., 2020). The development of BCF mainly in the eco-industrial parks is mutual with an industrial symbiosis approach (Zailan, 2020). It also promotes the sustainability of resources as the key pillar in the circular economy concept (Misrol et al., 2020). Taken the Tanjung Langsat Biomass steam plant, Malaysia that relies on palm oil mills (POM) biomass fuel such as empty fruit bunch (EFB), palm kernel shell (PKS), and mesocarp fibre (MSF) (Zailan, 2021). The BCF generates and selling steam as its core business. Generally, the BCF installation comes with challenges given as operational compliance and budget constraint. A reliable, uninterrupted steam supply is important to satisfy the steam requirement of tenants to meet their daily operation at any cost. The problem facing by the steam provider is the limitation of plant operators to plan for an optimal operation system including the efficient operation and maintenance (O&M) schedule. Annual planned outages duration shall be budgeting appropriately to ensure optimum yearly operation cost.
Several researchers have optimized operation costs concerning O&M costs in energy industries. It includes an optimization framework for the maintenance program of a power station (Tam et al., 2007). The pellet production used in the BCF had optimized to reduce the O&M costs (Rentizelas et al., 2014). In the POM biomass field, Tan et al. (2020) developed an optimal POM complex concentrating on POM effluent. Hence, this work has been conducted to fill in the research gap in a POM-based BCF development whereby a recent optimization model has to be developed considering operational optimization and maintenance schedule time constraints. The objective of this study is to develop an optimization model of POM-based BCF considering fuel cost,

Paper Received: 25 May 2021; Revised: 26 August 2021; Accepted: 25 November 2021
Please cite this article as: Zailan R., Lim J.S., Sa'ad S.F., Jamaluddin K., Abdulrazik A., 2021, Optimal Biomass Cogeneration Facilities Considering Operation and Maintenance, Chemical Engineering Transactions, 89, 517-522 DOI:10.3303/CET2189087

electricity cost and maintenance cost using General Algebraic Modelling System (GAMS) software (GAMS, 2021). The optimization model also aims to minimize total annual operation costs and to ensure tenants can depend on reliable, uninterrupted steam as they deserved from the BCF. Through this model, managers and engineers can direct the BCF to create lower annual operation costs. Besides, the planned annual maintenance program has been scheduled to investigate major faults or failures of the BCF system.

2. Methodology

The initial step of the methodology is the data collection for the generation of steam/power for selected BCF. Secondary data were acquired from previous studies, and some were collected during a field survey at the selected BCF including fuel, electricity, operating characteristics, tenant heat demand, and O&M. The model requires a balanced supply and demand relationship between the BCF and the tenants to meet steam demand. Next, the superstructure has been developed as in Figure 1 and followed with the formulation of the optimization model. In this study, given a component of multi-POM biomass to operate a BCF. Fuel input for the BCF had opted POM biomass that is EFB, PKS, and MSF. Steam generation consists of high-pressure (HP) steam that will distribute to the respective tenants. Some portion of the HP steam will be let down to meet their medium pressure (MP) and low-pressure (LP) steam usage. In turn, the remaining HP distributes to the steam turbine for power generation. The generated electricity utilized by the BCF and could reduce the dependence on electricity from the grid system. A case study of POM-based BCF was modelled followed by a sensitivity analysis.

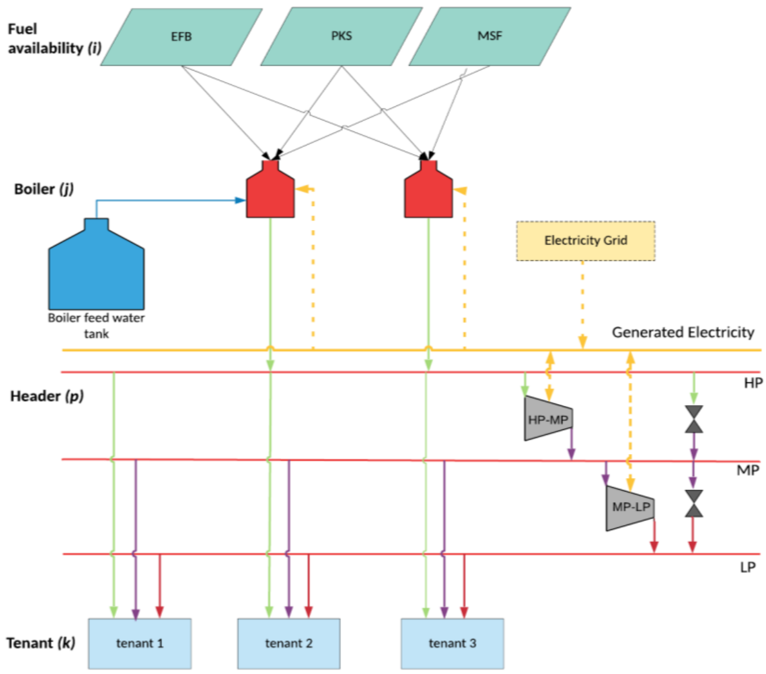

Figure 1: The superstructure of palm oil mill biomass cogeneration system

Objective function is to minimize the annual operation cost of the BCF operation through the optimal maintenance outages frequencies and intervals of the BCF. The operation cost is a summation of variable costs; fuel, boiler feedwater, outsource electricity generation, and maintenance. The mathematical model is as expressed in Eq(1).

$$MINANNCOST = ANFUELCOST + ANBFWCOST + ANOUTELECTCOST + ANMAINTCOST \quad (1)$$

The amount of boiler feedwater consumed in the boiler *j*, $MBFW_j$ is determined knowing the amount of HP steam generated including the percentage of water blown down from the boiler, $bdper$ according to Eq(2).Then, it is calculated as a one-year, $tyear$ boiler feedwater supply, $ANNBFW$ to the BCF as shown in Eq(3).

$$MBFW_j = MHP_j/(1-(\frac{bdper}{100})) \qquad \forall j \quad (2)$$

$$ANNBFW = MBFW \times tyear \tag{3}$$

The amount of fuel $MFUEL_{i,j}$ entering the boiler *j,* is sufficient to generate a specified amount of HP steam. It must be satisfied by the fuel availability, $fuelavail_i$ as shown in Eq(4).

$$\sum_j MFUEL_{i,j} \leq fuelavail_i \qquad \forall i,j \tag{4}$$

An energy balance in the boiler component is as in Eq(5) which the amount of energy into the boiler *j*, $EINBOIL_{i,j}$ is equal to the fuel entering the boiler *j,* $MFUEL_{i,j}$ and the net heating value of the fuel consumption, nhv_i. Noted that the exact energy generated from the fuel consumption relies on the boiler efficiency, $boileff$.

$$EINBOIL_{i,j} = MFUEL_{i,j} \times nhv_i \times boileff \qquad \forall i,j \tag{5}$$

Energy flows out from the boiler *j,* $EOUTBOIL_{i,j}$ is determined by the amount of HP steam generated and the enthalpy difference between boiler feed water, h^{BFW} and HP steam, h^{HP}.

$$EOUTBOIL_{i,j} = MHP_j \times (h^{HP} - h^{BFW}) \qquad \forall i,j \tag{6}$$

At the tenant's demand side, Eq(7) implied that the supply of steam $MPC_{p,k}$ must greater than heat demand $heatdem_{p,k}$ of every tenant to ensure stable and uninterrupted steam supply.

$$MPC_{p,k} \geq heatdem_{p,k} \qquad \forall p,k \tag{7}$$

To reduce the operation cost on the utility side, the BCF is practicing self-generation of electricity. The amount of electricity generated by the steam turbine as given in Eq(8) and Eq(9). The boiler operation for the steam generation process consuming electricity generated from the in-house power generator. In this model, electricity requirement, $ELECTDEM$ only considers electricity consume by boilers, boiler control system, and steam turbine. Eq(10) shows the total electricity demand by the BCF. In case of insufficient electricity, $OUTELECT$ is outsourcing from the grid system and calculated as Eq(11). Finally, Eq(12) is used to annualize the total electricity supplied by the grid system.

$$ELECTGEN^{HPMP} = MTURBHP \times (h^{HP} - h^{MPT}) \times turbeff/3600 \tag{8}$$

$$ELECTGEN^{MPLP} = MTURBMP \times (h^{MPT} - h^{LPT}) \times turbeff/3600 \tag{9}$$

$$ELECTDEM = boilelect + boilcontelect + stelect \tag{10}$$

$$OUTELECT \geq ELECTDEM - (ELECTGEN^{HPMP} + ELECTGEN^{MPLP}) \tag{11}$$

$$ANNOUTELECT = OUTELECT \times tyear \tag{12}$$

An O&M cost model deliberately used to assess the effectiveness of O&M at the typical BCF. This model was developed by Tam et al. (2007) and adopted in this study. The following constraints shall consider where the outage dimension cost, ODC is crucial. It means the cost of loss of operation due to planned maintenance outages. Eq(13) expressed the ODC .

$$ODC = sdt - not \times TEARN \times {}^{1}/_{MI} \tag{13}$$

where, not is system non-operating time, referring to the amount of time when the system is not operating due to equipment failure. In this study, non-operating time is equal to zero. MI is maintenance interval (in a year), sdt is system downtime for maintenance or planned outages days duration per outages. Meanwhile, $TEARN$ is the total daily earning without outages as calculate in Eq(14), where amount of steam generated multiply with steam price, $steamsale$.

$$TEARN = \sum_j MHPSTEAM_j \times 24 \times steamsale \tag{14}$$

Next, resource dimension cost, $REDC$ or the cost needed for performing maintenance action typically consist of human resource, $HUMRES$ and equipment and tools, $EQUIPCOST$. The equation is express in Eq(15).

$$REDC = HUMRES + EQUIPCOST \tag{15}$$

Finally, the $ANMAINTCOST$ in Eq(16) represents sum of all two dimensions costs referring to the total annual maintenance cost for the BCF.

$$ANMAINTCOST = ODC + REDC \tag{16}$$

3. Case study

As for case study, the core business of the designated POM-based BCF is a steam generation and selling to the tenants. It also commits electricity generation for the plant's in-house use. Thus, the steam and electricity generation components are the main perspectives in this cost optimization model. This model is an extension from the baseline case study in Zailan et al. (2020) where the power generation is newly introduced. The number of boilers also increased to two units. All parameters and variables employed in this model are set hourly and subsequently multiplied into the annual cost. Boiler fuel is accessible from the POM biomass supplier that is EFB, MSF, and PKS. Table 1 presents data for cost, heating value, and fuel availability. Two units of water tube boilers are operating continuously at the BCF. Each boiler generates 50 t/h of steam. The installed backpressure steam turbines are HP-MP and MP-LP and able to generate electricity up to 1 MWh. The engagement of the heat supplier-tenant concept is applied to execute this model. On the demand side, the amount of steam selling to the tenants presented in Table 2.

Table 1: Palm oil mill biomass fuel data

Fuel	Heating value (Mj/t) (Hamzah et al., 2019)	Cost of fuel (MYR/t) (Liew et al., 2017)	Availability (t/h) (Md Jaye et al., 2016)
EFB	18,800	22	300
MSF	19,060	36	180
PKS	20,090	120	120

*1 MYR equals to 0.24 USD

Table 2: Selling steam to tenant

Tenant	HP Steam (t/h)	MP Steam (t/h)	LP steam (t/h)
1	20	20	0
2	0	10	20
3	10	0	10

Energy consumption data for proposed components will determine how much electricity to outsource from the grid system. The amount of electricity consuming by the boilers is 0.44 MWh while the steam turbine 1.6 MWh. The baseline data for O&M to determine the optimality of this model is as in Table 3. Assigned equipment and human resource costs were estimated based on the plant survey at the biomass cogeneration plant. The planned maintenance is once a year with seven days outage as suggested by Myriad (2021) includes setting up maintenance work to allow cooling down of a boiler prior to major cleaning process.

Table 3: Operation and maintenance data for annual maintenance program

Detail	Description
Maintenance Duration (Baseline) (d)	7
Maintenance Interval (Baseline) (In a year)	1
Equipment Cost (MYR/y)	100,000
Human Resource cost (MYR/y)	30,000

*1 MYR equals to 0.24 USD

4. Results and discussions

The case study data were fitted into the developed MILP model and optimized using the CPLEX solver of GAMS Studio 1.3.4. It was run on a personal computer using Mac OS X at the solution time 0.01 s. Model statistics has a total of 67 constraints, 63 single variables, and 160 non-zero elements. The optimal operation of BCF illustrates in Figure 2. Total fuel consumed by the BCF system is 32.06 t/h for each boiler and generates 90 t/h of steam. The mass flow rate of EFB, MSF, and PKS that entering the boiler at optimal operation is 10.97 t/h, 10.82 t/h, and 10.27 t/h. Whereby the electricity generated from both turbines is 0.5 MWh. The electricity generated will be supplied to the BCF components about 2.04 MWh. An insufficient electricity amount of 1.53 MWh is to be outsourcing from the grid system. Given the annual operating hours for the BCF is 7,056 h. Overall, the annual electricity requirement is 14,394.2 MWh/y. Annual electricity generation is 3,556.2 MWh/y and requires about 10,828 MWh/y outsource electricity. All tenants receive sufficient steam generated from the boilers and supplementary steam from the turbine operation. Hence, the steam pass through the pressure reduction valves, HP and MP reduction valves are negligible. Annualized costs attributed to the optimal annual operation cost of this model are present in Table 4. Comparison with the baseline model without power generation (90 t/h steam generation), a total of annualized costing is cheaper at MYR 32,113,292 (2.7 %). A reflected minor difference would be an opportunity to generate power in the BCF to reduce dependency on-grid system. Detail economic analysis suggested considering an investment of steam turbine and auxiliary components to produce a quantifiable profit.

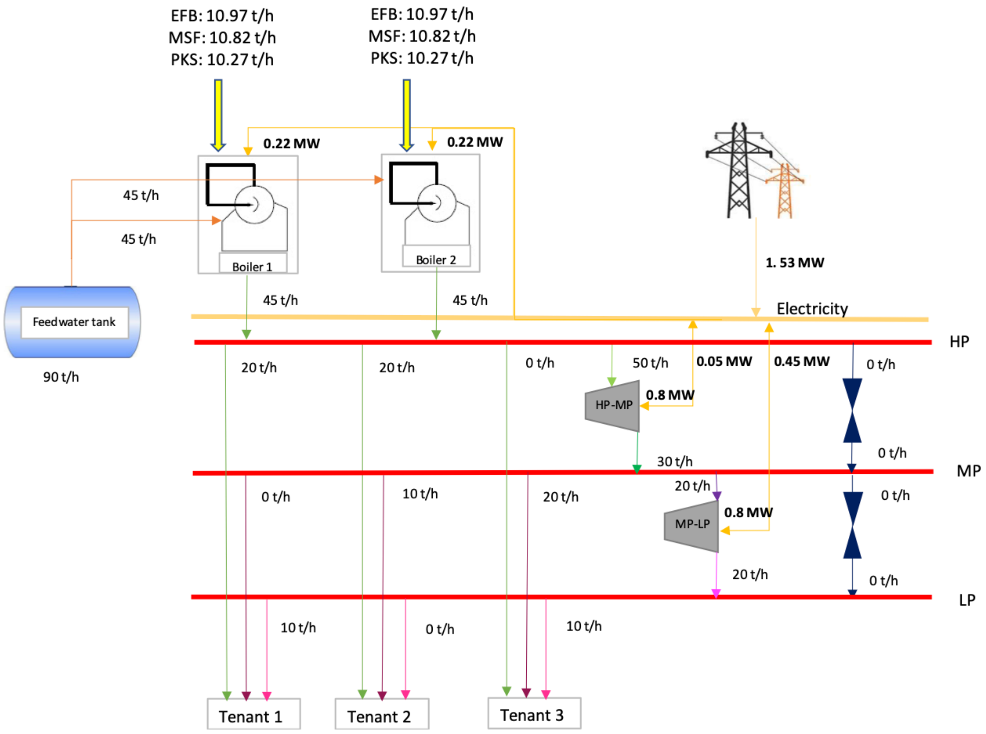

Figure 2: The optimal palm oil mill biomass cogeneration system

Table 4: Cost breakdown for optimal palm oil mill biomass cogeneration system

Item	Value (MYR/y)
Annual fuel	26,299,382
Annual boiler feedwater	1,905,120
Annual outsource electricity	3,898,080
Annual O&M	886,000
Total	32,988,582

*1 MYR equals to 0.24 USD

Sensitivity analysis aims to examine the effect of the input variable on the performance of the base case condition. According to the cost breakdown provided in Table 4, the highest cost of annual fuel and outsource electricity make it significant to assess its impact on annualised cost. The sensitivity bound is varying from the optimal values about $\pm$10 %. Total annual fuel cost acquired from fuel cost variations (MYR 23,669,444 and MYR 28,929,321) while the total outsources electricity cost varying with different electricity tariffs (MYR 324/MWh and MYR 396/MWh). Meanwhile, maintenance duration were tested for 6 and 8 d and interval 0.9 and 1.1 to assess impact of maintenance schedule. The sensitivity results portrayed in Figure 3, whereby the impact of each parameter towards the changes in annualised cost is noticeable. An annualised cost is highly impacted by the fuel cost (±8 %), electricity cost (±1.2 %), (maintenance duration (-0.8 % & 0.3 %), followed by the maintenance interval (0.26 % & -0.27 %). Longer maintenance intervals (1.1) poses a significant reduction of annualised cost. This condition is expecting to increase the effectiveness of an outage and reduce the failure risk (Tam, 2007). Further studies are appealing to attain the trade-off between the profit and operation cost.

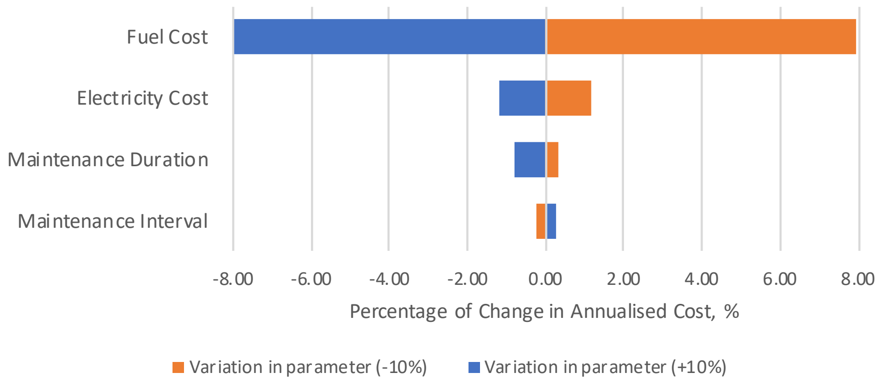

Figure 3: Sensitivity analysis of annualised cost of palm oil mill biomass cogeneration system.

5. Conclusion

An optimal operation of BCF ensure tenants received sufficient heat demand and practised self-generation electricity for in-house use. The sensitivity analysis presented impacts from cost of fuel and electricity, maintenance duration and maintenance interval to the annualised cost. The optimization model requires a trade-off between the cost and profit of the BCF in a future BCF business model of selling steam and electricity. Future optimization also open to explore ash management and the environmental impact of the BCF.

Acknowledgment

The authors thank funding from Universiti Teknologi Malaysia (UTM) via grant Q. J130000.2451.08G48 and R. J130000.7851.5F388.

References

Abbas T., Issa M., Ilinca A., 2020, Biomass cogeneration technologies: A review, Journal of Sustainable Bioenergy Systems, 10(1), 1-15.

GAMS, 2021, An introduction to GAMS, General Algebraic Modeling System <https://www.gams.com> accessed 19.06.2021.

Hamzah N., Tokimatsu K., Yoshikawa K., 2019, Solid fuel from oil palm biomass residues and municipal solid waste by hydrothermal treatment for electrical power generation in Malaysia: A review, Sustainability, 11(4), 1060.

Jaye I.F., Sadhukhan J., Murphy R.J., 2016, Renewable, local electricity generation from palm oil mills: a case study from Peninsular Malaysia, International Journal of Smart Grid and Clean Energy, 44, 106-111.

Liew W.L., Muda K., Azraai M., Affam A.C., Kheang S., 2017, Agro-industrial waste sustainable management–a potential source of economic benefits to palm oil mills in Malaysia, Journal of Urban and Environmental Engineering, 11(1), 108-118.

Misrol M.A., Alwi S.R.W., Lim J.S., Manan Z.A., 2020, An optimal water-waste nexus for an eco-industrial park, Chemical Engineering Transactions, 81, 643-648.

Myriad, 2021, Myriad Guide to Servicing Biomass Boiler, Myriad Heat & Power Products <myriadservice.co.uk/biomass-servicing-requirements> accessed 19.06.2021.

Rentizelas A.A., Tolis A.I., Tatsiopoulos I.P., 2014, Optimisation and investment analysis of two biomass-to-heat supply chain structures, Biosystems Engineering, 120, 81-91.

Tam A.S., Price J.W., Beveridge A., 2007, A maintenance optimisation framework in application to optimise power station boiler pressure parts maintenance, Journal of Quality in Maintenance Engineering, 13(4), 364-384.

Tan Y.D., Lim J.S., Alwi S.R.W., 2020, Optimal design of integrated palm oil complex with palm oil mill effluent elimination strategy, Chemical Engineering Transactions, 78, 1-6.

Zailan R., Saad S.F., Jamaluddin K., Alwi S.R., Shiun L.J., Tan Y.D., Mohamad S.N., Lawal M., Misrol M.A., Kuba N.S., Reba M.N., 2020, Towards Eco-Industrial Park in Malaysia: Promising Opportunities, Challenges and Regulator Roles, International Journal of Psychosocial Rehabilitation, 24(1), 562-570.

Zailan R., Lim J.S., Manan Z.A., Alwi S.R., Mohammadi-ivatloo B., Jamaluddin K., 2021, Malaysia scenario of biomass supply chain-cogeneration system and optimization modeling development: A review, Renewable and Sustainable Energy Reviews, 148, 111289.