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OPTIMAL STRATEGIES FOR A TECHNO-ECONOMIC AND ENVIRONMENTAL EFFICIENT ALGAL BIOREFINERY

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ABSTRACT

Microalgae-based biomass are an emerging technology and an alternative source to biofuels. It has a high lipid content and is composed of other bio-compounds which is essential for high-valued products. The biorefinery concept is a means to efficiently convert microalgae into biofuels and other high-value products. However, biorefineries require large capital investments that must be wisely planned and decided across the lives of the investments. This study proposes a multi-period multi-objective mixed integer non-linear programming (MINLP) model that simultaneously maximizes net present value (NPV) and minimizes greenhouse gas (GHG) emissions through optimal investment scheduling and operational decisions of an algal biorefinery. The model capabilities are demonstrated through an illustrative case study and scenario analysis.

Keywords: algal biorefinery, mixed integer non-linear programming (MINLP), multi-objective optimization

1. INTRODUCTION

Current energy production through the use of non-renewable fossil fuels, especially in the face of rising energy consumption trends, is expected to result in a devastating energy crisis within the next few decades. Additionally, its greenhouse gas (GHG) emissions contribute to environmental damage and potential health problems in surrounding communities. Hence, much attention has been focused on exploring the use of carbon-neutral and renewable energy sources such as biomass [1]. In particular, microalgae present as an attractive alternative to traditional energy sources because it does not compete with conventional agriculture, and have high biofuel yield for every unit of the land area due to high photosynthetic efficiency [2]. Moreover, microalgae have the potential for co-production of valuable non-energy products, such as carbohydrates, lipids, proteins, antioxidants, and pharmaceuticals among some. Biorefineries are a promising concept of transforming microalgae-based biomass into biofuels and high value-added products [3].

Nonetheless, despite the potential of its benefit, the significant capital investments required still hinder its large-scale commercialization [2]. Hence, it is important to develop strategies for the economic and eco-efficient production of bioenergy to meet future energy and fuel demand. The design of biorefineries requires a systematic approach because the process components are highly interdependent. Proper management tools are needed to ensure that the potential benefits (e.g. reduced land requirements and environmental impact) are realized while preventing the possibility of increased resource consumption [4]. Several studies have proposed optimization modeling for the synthesis of biorefineries [4,5]. However, these studies overlooked the need to assess the feasibility of investments across multiple periods. Single period models are inaccurate

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representations of actual systems due to the limitations of interactions that exist between time intervals. This is evidently true especially in committing to large capital investments on a long-term time-horizon considering the varying supply and demand levels, prices and costs. Thus, multi-periodicity should be considered in the model formulation to capture realistic biorefinery systems that are developed and used for several periods. With this, the effect of shifts in the biorefinery's conditions on investment and operational decisions can be considered. As an example, when there is a significant upward shift in demand, the system may choose to respond by expanding the capacity of relevant process units, or producing to stock in earlier periods if holding costs are cheaper than investment costs. Additionally, it is possible that future demand for products is not enough to justify investing in or expanding the capacity of certain interdependent process units; in this case, it may be better for the system to source input requirements externally.

Furthermore, multi-objective optimization models on similar systems handle each of the objectives separately, wherein one objective is treated as the objective function, while the other serves as a constraint [4], or assume user-defined upper and lower bound limits for the objectives [5]. These approaches may be improved because it limits the performance on the system to the defined constraints, when a better solution may exist. Goal programming methods are appropriate for simultaneously optimizing two or more conflicting objectives, and ensure that the best Pareto optimal solution is achieved with minimal computational effort [6]. Rollan et al. [7] proposed a goal programming formulation to handle two conflicting objectives; however, their approach is limited because it compares the performance of the model on the two objectives on different scales. This issue is addressed in the studies of San Juan et al. [8, 9], but is not able to capture the different priorities of stakeholders on the objectives. Thus, the model proposed in this study will optimize investment and operational decisions of an algal biorefinery based on multiple weighted objectives across multiple planning horizons.

2. PROBLEM DEFINITION

The problem statement is formally defined as follows. An algal biorefinery, which will be studied across t years, comprises of m process units and n material streams. These material streams flow through process units represented by the parameter A_{mn}, where a negative entry means a stream is consumed by the process and a positive entry signifies a stream is generated by the process. Each material stream has a corresponding unit selling price (p_n), final demand (d_{nt}), unit holding costs (h_n) if kept in inventory, and unit purchase costs if acquired externally (v_{nt}). However, the amount of material that may be purchased on the market is limited by the available supply each period (s_{nt}). There is also fixed costs associated with investing (a_m) on, operating (f_{mt}) a process unit. Additionally, each process unit has an associated variable operating cost (u_{mt}) proportional to utilized capacity (x_{mt}), which has an upper limit represented by c_{mt}. This capacity limit may be expanded by e_{mt} given a corresponding proportional cost q_m and a fixed expansion cost k_{mt}. Each process unit also generates GHG emissions, represented by E_m, proportional to utilized capacity. The objective is to determine the amount of material n to source (denoted by w_{nt}), whether or not to invest on a certain process unit and period (b_{mt}), whether to operate a process unit on a particular period (y_{mt}) and the amount of capacity to utilize (denoted by x_{mt}), and whether to expand the capacity of process unit m on a certain period (r_{mt}) and extent of the expansion (e_{mt}) such that the NPV (represented by P) is maximized and total cumulative GHG emissions (expressed by G) is minimized simultaneously.

3. MODEL FORMULATION

The MINLP model for the algal biorefinery under study is given by Equations (1)-(14), wherein the overall objectives are to maximize the NPV and minimize the GHG emissions of the system throughout the planning horizon.

Equation (1) ensures the simultaneous optimization of the model's performance on both of its objectives, which are to maximize NPV and minimize GHG emissions by maximizing the lower performance rate between the two. This prevents the model from optimizing one objective at the expense of the other; achieving a balance between the two. Performance rates are the quotient between improvement realized (difference between worst and actual values) and the potential improvement (difference between worst and potential values). Potential objective values (P_{pot} and G_{pot}) are determined by optimizing each corresponding objective as single objective optimization models, while the worst values are obtained when the other objective is optimized. Particularly, the worst value for NPV (P_{min}) is its value when energy consumption is minimized, while the worst value for GHG emissions (G_{max}) is its value when NPV is maximized alone. The weights which are represented by parameter z based on relative importance, may be multiplied to the performance rates to consider priority rankings of the objectives.

$$\max\min\left[z_P\left(\frac{P-P_{min}}{P_{pot}-P_{min}}\right), z_G\left(\frac{G_{max}-G}{G_{max}-G_{pot}}\right)\right] \quad (1)$$

$$P = \sum_t(-F_t + R_t - V_t)(1+i)^{-t} \quad (2)$$

$$R_t = \sum_n p_n(d_{nt} - g_{nt}) \qquad \forall t \quad (3)$$

$$F_t = \sum_m(b_{mt}a_m + y_{mt}f_{mt} + r_{mt}k_{mt}) \qquad \forall t \quad (4)$$

$$V_t = \sum_n(w_{nt}v_{nt} + h_nI_{nt}) + \sum_m(x_{mt}u_{mt} + e_{mt}q_m) \qquad \forall t \quad (5)$$

$$G = \sum_t\sum_m E_my_{mt}x_{mt} \quad (6)$$

The NPV, as given by Equation (2), sums the net cash flows each period projected to their present worth through the interest rate i. The net cash flow is a function of revenues (R_t) less fixed (F_t) and variable (V_t) costs. Equation (3) defines revenues as the product between material prices and amount of demand satisfied, which is the difference between the end demand for a material and unsatisfied demand which is denoted by g_{nt}. While Equation (4) describes fixed costs to be dependent on investment costs for installing a process unit, and fixed costs to operate and expand the capacity of the process units. Variable costs shown in Equation (5) include costs to purchase material as input to the system, to hold inventory, and to utilize and expand the capacities of process units. The second sub-objective of the model is to minimize the system's total GHG emissions as shown in Equation (6), which is proportional to the emissions from each process unit and utilized capacity of that unit.

$$w_{nt} \leq s_{nt} \qquad \forall nt \quad (7)$$

$$\sum_m A_{mn}y_{mt}x_{mt} + w_{nt} + I_{nt-1} - I_{nt} + g_{nt} = d_{nt} \qquad \forall nt \quad (8)$$

$$x_{mt} \leq c_{mt}y_{mt} \qquad \forall mt \quad (9)$$

$$c_{mt} + e_{mt} = c_{mt+1} \qquad \forall mt \quad (10)$$

$$e_{mt} \leq Qr_{mt} \qquad \forall mt \quad (11)$$

$$\sum_0^t b_{mt} \geq \sum_t^T y_{mt} \qquad \forall mt \quad (12)$$

$$w_{nt}, x_{mt}, e_{mt}, I_{nt}, g_{nt} \geq 0 \quad (13)$$

$$b_{mt}, y_{mt}, r_{mt} \in \{0,1\} \quad (14)$$

The constraints include sourcing limits based on supply availability, expressed by, as defined by Equation (7). Equation (8) computes for demand satisfaction through material and energy balances given by the first term of the equation based on a process technology matrix, additional material sourced externally (in the second term), and carried over from the previous period (third term). The fourth and fifth term of Equation (8) allow for production and supply to overshoot the demand by storing the excess in the inventory (denoted by I_{nt}) or to miss the demand, respectively. Equation (9) restricts the capacity of a process unit that may be utilized each period by its upper bound capacity, which is defined in Equation (10) as dependent on capacity expansions performed from the previous period. The binary variables for capacity expansions are switched on in Equation (11). Meanwhile, Equation (12) requires a process unit to initially be installed before they can be operated. Lastly, Equations (13)-(14) impose non-negative and binary constraints to relevant variables. Non-linearities exist in the model from the product between continuous variable x_{mt} and binary variable y_{mt}, and between continuous variable c_{mt} and binary variable y_{mt} in Equations (6), (8), and (9) to ensure that the capacity of a process unit may only be used when the unit is operating, and signals if a corresponding fixed operating costs needs to be paid.

4. COMPUTATIONAL EXPERIMENTS

Computational experiments were carried out using IBM ILOG CPLEX Optimization Studio in MATLAB on a MacBook Pro with a 3.1 GHz Intel Core i5 processor and 8 GB 2133 MHz LPDDR3 RAM. Non-linear equations were linearized to facilitate this.

The algal biorefinery system includes five main processes which are the integrated microalgae-to-biodiesel plant, the anaerobic digestion unit, the combined heat and power plant, the methanol production plant, and the biochar production unit as depicted in Fig. 1. The system is studied across a 10-year planning horizon. The proposed model can be used to select between different equipment and biofuel feedstock, which is simply done by including process units or steps for upstream processes such as cultivation, harvesting, and drying. However, this study covers a system that has pre-identified microalgae as the feedstock for biodiesel. Wherein the biodiesel production plant is treated as a single process unit or black box that performs all necessary process to produce biodiesel as its final output. This system and the corresponding data parameters were adapted from related literature [4, 5].

It is necessary to run the proposed model wherein each objective component (maximizing NPV and minimizing GHGs) are optimized individually to obtain the possible best and worst values for NPV and emissions required to run the full model, which will simultaneously optimize both objectives. Having the best and worst values for either the objectives will allow for the setting of achievable goals and for an unbiased evaluation of

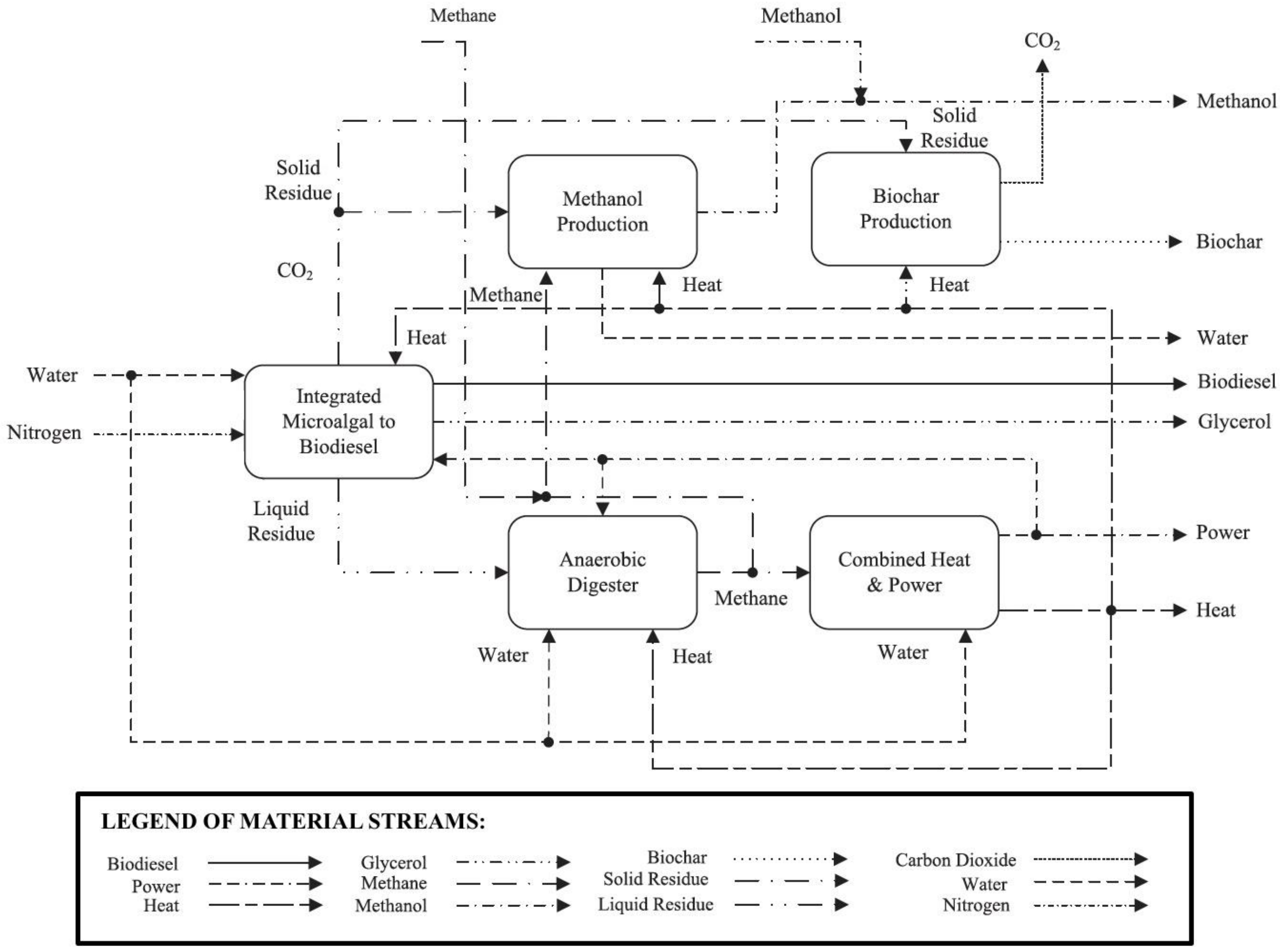

Fig 1 Process flowsheet of the polygeneration system

Table 1. Summary of optimal objective values

	Maximizing NPV		Minimizing Emissions		Complete Model Run	
		Rating		Rating		Rating
NPV (US$)	2.44×10^{12}	1	6.60×10^{10}	0	2.37×10^{12}	0.9676
Emissions (kg CO_2 - eq)	7.44×10^{11}	0	1.18×10^{11}	1	6.62×10^{10}	0.9997

goal attainment performance. The values of the objectives in the three runs are compared in Table 1.

When NPV is maximized solely, the highest achievable NPV for the biorefinery system is US$ 2.44 x 10^{12}. In this scenario, the model makes sure to satisfy most of the product demands. In particular, the biorefinery prioritizes the production of biodiesel and glycerol from microalgae because they have the highest selling price among all products. However, because the costs to keep biodiesel in inventory is relatively cheaper than the fixed costs needed to operate the plant, biodiesel should be produced on the earlier periods and kept to satisfy demand on latter periods. The other process units, particularly the biochar plant, combined heat and power plant, and anaerobic digestion unit were selected to supply the integrated microalgae-to-biodiesel plant with required power, heat, and methane inputs, while the excess materials were used to satisfy end market demands. Since the methanol production plant is expensive to operate, the system opts to satisfy the methanol requirements and demand by purchasing the product externally. Nonetheless, the operation of the integrated microalgae-to-biodiesel plant and other process units which contribute significantly to the GHG emissions have sacrificed the environmental objective in pursuit to maximize the NPV.

On the other hand, when GHG emissions is minimized exclusively, the optimal strategy is to operate the biorefinery only on the first period. Specifically, the microalgae-to-biodiesel plant and biochar plants are operated. Biodiesel and glycerol demand for all periods are produced immediately, and this is sufficient to ensure that a positive NPV is achieved. GHG emissions is reduced significantly compared to the first scenario because the biorefinery process units are no longer operated in the succeeding periods, and the biochar plant has resulted in a reduction in carbon dioxide emissions. However, as a consequence, the NPV decreases significantly because the demand for other products are left unsatisfied.

When both objectives are simultaneously optimized, Table 1 presents objective values that are closer to the best potential value. Specifically, the solution of the full model achieves the goals at a performance rating of 0.9676. In an effort to jointly increase NPV and decrease emissions, the system becomes more careful in selecting process units it should invest in and when they should be utilized. As a result, the amount of products held in stock increases as the model becomes wiser in weighing production costs and emissions, and purchasing costs. In this scenario, the system chooses the integrated microalgae-to-biodiesel plant, the anaerobic digestion unit, and the biochar plant. The multi-objective model realizes greater NPV compared to when the environmental objective is minimized exclusively because it ensures that higher proportion of the demand for other high-value products are satisfied through production within the biorefinery.

5. CONCLUSIONS AND RECOMMENDATIONS

A multi-objective multi-period optimization model which captures investment planning, operational decisions, and expansion opportunities for an integrated algae biorefinery was proposed in this study. The two objectives of the study, which were to maximize NPV and minimize GHG emissions were handled using a goal programming approach, which allowed a balance to be achieved between the two conflicting objectives. The capabilities of the proposed model were demonstrated through a case study. The results of the model implementation showed that it may be better for the biorefinery to source some of its material requirements externally, instead of investing in process units to produce these products. Furthermore, in some cases, fixed operating costs are more expensive than costs to store the products, thus; the system chooses to produce in excess for future demand. The proposed optimization model may be useful to plant owners, managers, engineers, and other relevant stakeholders in deciding on the final design of their biorefinery, particularly, when specific investments would have to be made, and the capacity of each process unit to utilize each period. Furthermore, the model also has the ability to capture varied stakeholder priorities on each objective. The decision-makers can evaluate several designs that meet their objective goals. Extensions to this work can focus on extending the application to a more detailed system or supply chain capturing environmental impacts not limited only to GHG emissions. Additionally, algae is sensitive to contaminations that may negatively impact its viability as a biofuel feedstock; thus, the model may be extended to be robust against uncertainties in biomass supply and quality.

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NOMENCLATURE

Indices	
m	Process units
n	Material streams
t	Time period
Parameters	
P_{min}	NPV value when GHG emissions is minimized
P_{pot}	Maximum achievable NPV
G_{max}	GHG emissions when NPV is maximized
G_{pot}	Minimum achievable GHG emissions
a_m	Investment cost of process unit *m*
f_{mt}	Fixed cost to operate process unit *m* on period *t*
k_{mt}	Fixed cost to expand the capacity of process unit *m* on period *t*
p_n	Selling price of material *n*
d_{nt}	Final demand for material *n* on period *t*
v_{nt}	Cost of material *n* on period *t*
h_n	Unit holding cost for material *n*
u_{mt}	Cost to operate process unit *m* on period *t*
q_m	Unit capacity expansion cost of process unit *m*
s_{nt}	Available supply of material *n* for purchase on period *t*
E_m	GHG emissions of process unit *m*
A_{mn}	Flow of material *n* through process unit *m*
Variables	
P	Net present value
G	Greenhouse gas emissions
F_t	Fixed costs on period *t*
R_t	Revenues on period *t*
V_t	Variable costs on period *t*
g_{nt}	Unmet final demand of material *n* on period *t*
I_{nt}	Ending inventory of material *n* on period *t*
c_{mt}	Capacity of process unit of *m* on period t
w_{nt}	Amount of material *n* sourced on period *t*
x_{mt}	Utilized capacity of process unit *m* on period *t*
e_{mt}	Capacity expansion of process unit *m* on period *t*
b_{mt}	Binary, 1 if the investment on process unit *m* is made on period *t*
y_{mt}	Binary, 1 if process unit *m* is operating on period *t*
r_{mt}	Binary, 1 if process unit *m* undergoes capacity expansion on period *t*