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Multi-Objective Target-Oriented Robust Optimization of Algal Biofuel Production Integrating Resource Recirculation

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The production of algal biofuels has long-time been proven as an applicable alternative for fossil fuels. Yet, its economic performance is challenged by the inexpensive costs of fossil fuels. To address this, integrating various processes to the system yields high-value bioproducts to increase profitability and sustainability. Looking towards a circular economy perspective, the recirculation of resource flows is utilized to meet economic and environmental sustainability through the reduction of waste. Since the recovery of resources used within the production system is unpredictable in terms of output, uncertainty regarding resource recovery is assessed. Previous modelling studies have not looked into the opportunity of integrating continuous recirculation and reuse of resources along with its corresponding output uncertainty. In this work, a novel multi-objective target-oriented robust optimization model is developed centered on an algal biofuel production system that simultaneously optimizes profit and environmental impact, integrates inputs and processes aimed towards a closed-loop system, adopts the principle of resource recovery and recirculation along with the uncertainty of resource recovery outputs. A case study is solved as proof of concept and to illustrate the design methodology, optimal solutions based on economic and environmental performance are analyzed. Scenario analysis is also performed to analyze system behavior under varying conditions. Results show that to get a minimum profit, the robustness index is greater than one indicating the model is very much flexible to sudden changes in demand.

1. Introduction

The continuous rise of worldwide energy consumption, being heavily dependent on fossil fuel usage, has become a global environmental concern due to its greenhouse gas emissions. This is an indication that more research into sustainable energy sources such as solar, wind, and biofuels is necessary. Biodiesel has been considered the main substitute for fossil fuel (Ahmad et al., 2011). Microalgae is recognised as one of the most valuable feedstock in the production of biofuel given its high productivity and carbon sequestration capabilities (Singh and Gu, 2010). Yet, the associated production costs of microalgal biofuels are much higher than that of fossil fuels and the biofuel process flow typically generate lots of waste including leftover biomass waste. To maximize biomass utilization, other bioproducts that can be produced from microalgae are introduced into the microalgal production system (Budzianowski, 2017). Existing studies have already investigated the integration of various processes to a microalgal biorefinery production system.

Although having been introduced to various conceptual models for a microalgal biorefinery, the mentioned studies have not presented a mathematical assessment of the zero-waste aspect of the biofuel production process. Wu and Chang (2019) looked into an integrated microalgal biorefinery with process system engineering standpoint using life cycle assessment (LCA) and techno-economic assessment (TEA) methodologies to evaluate the economic and environmental indicators for the system. Their proposed biorefinery system consists of bioenergies and bioalcohols with materials that are meant to ultimately cycle back as inputs to the current process. However, their study simply contributes an algorithm for multi-objective optimization yet does not include the outcome of the methodology. Looking into present optimization models regarding microalgal biorefineries, various researchers have investigated on resource recirculation. García Prieto et al. (2017) incorporated methanol recovery as well as leftover hexane from lipid extraction. This study focused on single objective minimization with profit as the main priority. Aside from that, wastewater, flocculant, and catalyst recovery processes were considered in a multi-objective optimization study by Solis et al. (2021). This study

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involved life cycle assessment (LCA) as the environmental impact calculation methodology. Yet, this research focused on a deterministic approach regarding the cost and environmental aspects of the biorefinery. Since production system behavior are subject to different factors, a steady production flow is unlikely and shall yield specific effects to the economic and environmental performance of the biorefinery. To address this, the target-oriented robust optimization methodology (TORO), developed by Ng and Sy (2014), has been applied by Sy et al. (2018) to an algal biorefinery to achieve robust optimal solutions that are immune to uncertainties in parameters. However, the study does not look into the reuse and recoveries of resources within the biofuel production system which can add more complexity to the production process and presents a different behavior with regards to flow of materials within the biorefinery. Based on the review conducted on present algal biofuel optimization studies, there is a need to develop a target-oriented robust optimization model on an integrated algal biorefinery that optimizes profit and environmental impact, and incorporates resource recirculation focusing on a zero-waste process flow.

2. System definition

The microalgal biorefinery system and the other components of the mathematical model are defined.

2.1 Microalgal biorefinery

The microalgal biofuel process network involves the main processes necessary for biofuel production, biochar production and anaerobic digestion processes for usage of leftover biomass, and recovery processes for the different input materials as presented in Figure 1.

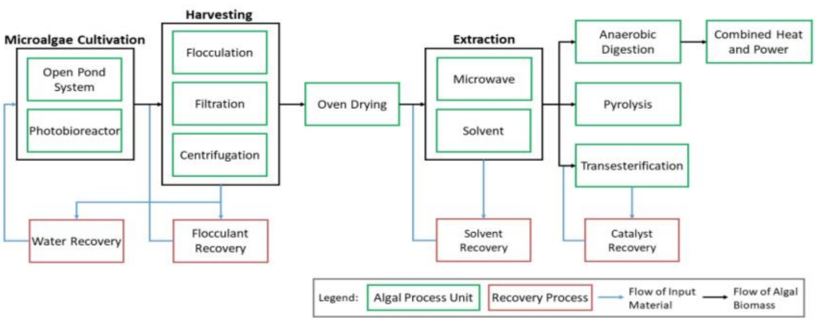

Figure 1: Microalgal biorefinery process network

The algal biofuel process flow to be considered in this study is divided into two main stages. The first stage is focused on microalgal biomass cultivation and the conversion of biomass into algal oil to be used in biofuel production. The main processes involved in this stage are microalgae cultivation, harvesting, oven drying, and lipid extraction. The second stage includes the downstream processes of the biorefinery focusing on the conversion of the biomass into end products such as biodiesel, glycerol, biochar, and digestate. The extraction process produces algal lipid which is transformed into biodiesel and glycerol through transesterification. Generated waste from the extraction process in the forms of solid and liquid residues. These residues are then converted into bioproducts such as biochar and digestate through pyrolysis and anaerobic digestion.

2.2 Resource recirculation

For the integrated algal biorefinery, material inputs such as water, flocculant, solvent, and catalyst are those that are involved in the resource recirculation consideration. This is because these are resources that simply assist in microalgal biomass development for biofuel conversion. Resource recovery process units are added to biorefineries to be able to recover materials if the model chooses to do so. Decisions shall then be made regarding the yield of the waste input determining whether the material is reused in the production system, sold for a given price per kg, or led to waste.

2.3 Multi-periodicity

The optimization model considers multiple time periods to incorporate long term biorefinery operations. Capital and operating costs shall be properly accounted for the microalgal biorefinery with multiple period consideration.

2.4 Cost components

For the optimization model, the following cost components will be included namely: inventory costs, initial investment costs, operating costs, and material purchasing costs. Given that the optimization model considers multiple time periods, inventory costs are included for each material expressed as a periodic cost per kg material. Investment costs refer to the initial capital expenses incurred to construct the microalgal biorefinery process units expressed at a cost per facility basis. Operating costs include labor, overhead, and material costs associated with each process expressed as a cost per time period. Material purchase costs are set for every material input that is purchased for microalgal production expressed as a cost per kg unit.

2.5 Environmental impact components

The environmental impact values used for the minimization objective are greenhouse gas (GHG) emissions from the process units. Emission counts for each process are estimated at a rate of GHG emissions per output.

3. Model formulation

The mathematical optimization model is formulated with the objective functions and constraints are evaluated.

3.1 Assumptions

The production outputs of the biorefinery are assumed to be transported to customers instantaneously. The processing of microalgal biomass in all process units is instantaneous. Capacities for all facilities are fixed throughout the entire study period.

3.2 Objective functions

The objectives involved in the mathematical model are profit maximization and environmental impact minimization. The equation for profit is the difference between the revenue from all biorefinery products and the total costs incurred, presented in Eq(1). The total costs are broken down into capital costs, operating costs, purchase costs, and inventory costs. The environmental impact objective is defined in Eq(2).

$$\text{Profit} = \sum_t \sum_p SP_{pt} \cdot TP_{pt} - \sum_i FC_i \cdot BP_i - \sum_t \sum_i OC_{it} \cdot PO_{it} - \sum_t \sum_a PC_{at} \cdot MI_{at} - \sum_t \sum_a IC_{at} \cdot EI_{at} \tag{1}$$

$$\text{Environmental Impact} = \sum_t \sum_i EN_{it} \cdot PO_{it} \tag{2}$$

Given that the model has two objectives, there must be a balance between the economic and environmental objectives to generate the optimal solution. The objective function is defined as the maximization of the least desired value to balance the two objectives as seen in Eq(3) (San Juan et al., 2019). Since the objective function is nonlinear, linearizing constraints are necessary to make sure that the optimization model generates the optimal solution. The objective function is defined as the maximization of efficiency as seen in Eq(4). Eq(5) and Eq(6) indicate that the value for efficiency must be the minimum of the efficiencies of the two objectives.

$$\text{Max Z} = min\left[\frac{Profit_{worst} - Profit}{Profit_{worst} - Profit_{best}}, \frac{Impact_{worst} - Impact}{Impact_{worst} - Impact_{best}}\right] \tag{3}$$

$$\text{Max Z} = \text{Efficiency} \tag{4}$$

$$\text{Efficiency} \leq \frac{Profit_{worst} - Profit}{Profit_{worst} - Profit_{best}} \tag{5}$$

$$\text{Efficiency} \leq \frac{Impact_{worst} - Impact}{Impact_{worst} - Impact_{best}} \tag{6}$$

3.3 Constraints

The demand constraint for the different products of the biorefinery are presented in Eq(7). The total product outputs must be greater than or equal to the demand for each product namely, biodiesel, glycerol, biochar, and digestate. The capacity constraints define the processing capability of each facility as defined in Eq(8). The production output of each process must be less than or equal to the sumproduct of its process capacity and the binary variable for that process.

$$TP_{pt} \geq DB_{pt} \quad \forall p\ \forall t \tag{7}$$

$$PO_{it} \leq B_i C_i \quad \forall i\ \forall t \tag{8}$$

The conversion of product input to output is presented in the constraints shown in Eq(9). The product of the process input materials and the conversion matrix for input and outputs is set to be equal to the overall process outputs. For the flow of materials within the biorefinery, the relationship between the output of the previous process and the corresponding inputs for the next process is defined in Eq(10). The equation regarding the relationship between the total final products of the biorefinery and the outputs of the downstream processes is presented in Eq(11). The constraint about input ending inventory is defined in Eq(12). The ending inventory for a given period is equated to the total recovered input material for reuse during the given period. Eq(13) defines the input beginning inventory constraints per period. The beginning inventory for an input in a given period is the sum of the ending inventory of the previous period and the total purchased inputs during the current period.

$$XP_{ait}CM_{ai} = YP_{ait} \quad \forall a\ \forall i\ \forall t \tag{9}$$

$$\textstyle\sum_i YP_{ait} \geq \sum_{i-1} XP_{ait} \quad \forall a\ \forall i\ \forall t \tag{10}$$

$$\textstyle\sum_i YP_{ait} \geq TP_{pt} \quad \forall a\ \forall p\ \forall t \tag{11}$$

$$EI_{at} = RRI_{at} \quad \forall a\ \forall t \tag{12}$$

$$BI_{at} = EI_{at-1} + MI_{at} \quad \forall a\ \forall t \tag{13}$$

The relationship between the total required material input and the input usage for each process is displayed in Eq(14). Eq(15) displays that the input beginning inventory for each time period is greater than or equal to the total amount of required material input for production while Eq(16) indicates that the total amount of recovered material input is equal to the amount recovered going towards reuse, selling, and to waste.

$$RQI_{at} = \textstyle\sum_i XP_{ait} \quad \forall a\ \forall t \tag{14}$$

$$BI_{at} \geq RQI_{bt} \quad \forall a\ \forall t \tag{15}$$

$$\textstyle\sum_j YR_{ajt} \geq RRI_{at} + RSI_{at} + RWI_{at} \quad \forall a\ \forall t \tag{16}$$

The equation regarding the relationship between the total purchased material inputs and their corresponding purchase capacity is displayed in Eq(17). Similarly, Eq(18) presents the relationship between the total ending inventories of each input material and the corresponding inventory capacities. The equation pertaining to the binary variables for the process alternatives is displayed in Eq(19). As for the equation for relationship between binary variables of recovery processes and the corresponding main processes, it is presented in Eq(20). The equation setting the value for the input binary variables equal to the binary variable for the recovery of the given input material is presented in Eq(21).

$$MI_{at} \leq PK_{at} * BM_a \quad \forall a\ \forall t \tag{17}$$

$$EI_{at} \leq IK_{at} * BM_a \quad \forall a\ \forall t \tag{18}$$

$$\textstyle\sum_{process\ type} BP_i = 1 \tag{19}$$

$$BR_j = \textstyle\sum_i BP_i \quad \forall j \tag{20}$$

$$BM_a = BR_j \quad \forall a\ \forall j \tag{21}$$

3.4 Target-oriented robust optimization methodology

To execute the target-oriented robust optimization methodology, the robustness index shall be set as the new objective to maximize for the model as shown in Eq(22). Profit and environmental impact targets are set for the two objectives as presented in Eq(23) and Eq(24). The revised demand constraint is presented in Eq(25), which reflects the new demand values to be calculated using the robustness index. The new demand values are computed by subtracting the sumproduct of the robustness index and the demand threshold from the base demand values, as displayed in Eq(26).

$$\text{Max } Z = \alpha \tag{22}$$

$$\text{Profit} \geq Profit_{target} \tag{23}$$

$$\text{Impact} \leq Impact_{target} \tag{24}$$

$$TP_{pt} \geq \widetilde{DB_{pt}} \quad \forall p\, \forall t \tag{25}$$

$$\widetilde{DB_{pt}} = DB_{pt} - \alpha \cdot \widehat{DB_{pt}} \quad \forall i\, \forall t \tag{26}$$

4. Model validation

The mathematical model was validated using the Cplex optimization solver in the software MATLAB R2020a. The model is deemed valid since it runs according to the production system. For the base run, a study period of 10 years was arbitrarily selected. The process flow is presented in Figure 1.

4.1 Multi-objective optimization

The profit and environmental impact values for the base run are presented in Table 1. This illustrates the base values to be referenced for comparison to the target-oriented robust optimization runs. The final production network generated involves hybrid wastewater photobioreactor cultivation, filtration for harvesting, and microwave for extraction.

Table 1: Multi-objective optimization base run

Profit ($)	Environmental Impact – GHG (mPt)	Efficiency	Biodiesel Output (kg)
1,404,430.80	512.29	58.09 %	76,218.44

4.2 Target-oriented robust optimization

Upon executing the mathematical model with the additional equations for the TORO methodology, the optimal results are summarized in Table 2. The minimum set for the profit is set to 0 to indicate a breakeven production level. The optimal robustness index subject to the constraints and profit target is 1.094493. This indicates that the model is very flexible to changes in demand since it is greater than 1. It is seen that while there is near no profit, a significant amount of biodiesel production is still required compared to the base run result.

Table 2: TORO results summary

Profit ($)	Environmental Impact – GHG (mPt)	Efficiency	Biodiesel Output (kg)	Robustness Index
0.21	418.83	44.35 %	62,312.74	1.0945
1,000,221.03	485.39	53.94 %	72,216.24	0.3149
468,899.07	450.03	48.73 %	66,955.45	0.7290

Targets are set for the profit and environmental impact values to test how the mathematical model generates the robustness index. For a profit target of $ 1,000,000, the robustness index resulted to 0.31485. When the environmental impact target was targeted to be 450 mPt, the resulting index was then 0.729. This presents the effect of the profit target to resulting robustness capabilities of the system. A higher profit target leads to a lower robustness index which indicates that there is less room for error compared to a lower target.

To further observe the behavior of the optimization model under TORO, different values for the robustness index are assigned to generate the optimal results. Figure 2 presents the graph of the profit and environmental impact optimal values under the varying robustness indices. It is still evident that with lower robustness index, a higher profit value is expected since the model is less susceptible to changes in demand. Given a higher index, profit results to a lower value which may even lead to a net loss. The environmental impact has a positive correlation with profit yet a different behavior when the minimization objective is considered. With a higher robustness index, there is less impact which is desirable for the system. This indicates that it would then be the prerogative of the stakeholders to decide which objective to prioritize in the long run.

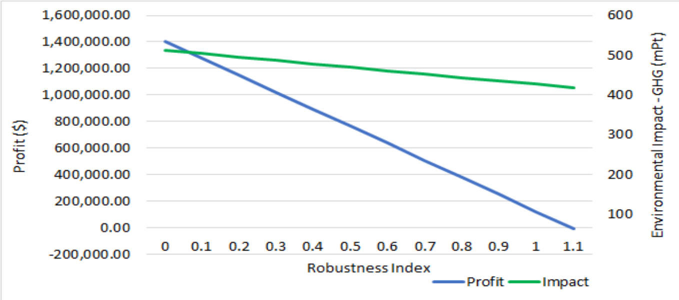

Figure 2: Profit and Impact vs. Robustness Index

5. Conclusions

This study introduced a multi-objective optimization model for an algal biorefinery involving resource recirculation with the goal of maximizing profit and minimizing environmental impact. The consideration of both objectives in a multi-objective optimization model strikes a balance between the two objectives. Target-oriented robust optimization is applied to the mathematical model to enable to it to become flexible to changes in demand. The optimal robustness index generated under a breakeven profit target is 1.0945 which indicates that the model is largely flexible to changes in demand given the target. Upon testing different robustness indices for the optimization model, it was found that a higher index yields a lower profit. On the other hand, a higher robustness index leads to a lower impact which is desirable for the biorefinery. This indicates that abrupt changes in demand affect the optimal results significantly which cements the importance of introducing robustness into the model.

Nomenclature

a, p – inputs & final products
BM_a, BP_i, BR_j – binary vars (input, process, recovery)
BI_{at}, EI_{at} – beginning and ending inventory
C_i, DK_{at}, IK_{at} – capacity (output, purchase, inventory)
DB_{pt} – demand
FC_i, OC_{it} – fixed costs and operating costs
IC_{at}, PC_{at} – purchase costs and inventory costs
SP_{pt}, TP_{pt} – selling price and total product amounts
PO_{it} – production outputs
mPt – millipoint
MI_{at} – purchase amounts
XP_{ait}, YP_{ait} – input and output material usage
CM_{ai} – conversion matrix for input/output
RQI_{at} – total required input
RRI_{at}, RSI_{at}, RWI_{at} – recovery decisions
t – time period
α – robustness index
i, j – process unit indices

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