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Optimal Allocation of Economic Benefits in an Eco-Industrial Park under Neutrosophic Environment

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Process integration is a technique that allows systems to be synthesized based on optimized component interactions. It can be applied to multiple plants to facilitate planning of industrial symbiosis. It involves the interactions created from the exchange of products and commodities rather than each plant obtaining their raw materials externally. Industrial symbiosis of multiple plants leads to higher economic benefits and reduced environmental impact. However, problems arise from the involvement of multiple owners of plants and the uncertainty in the demand of the end products. In this study, a neutrosophic mathematical programming model is developed to capture the behavior of decision-makers considering sharing economic benefits. The neutrosophic nature of profit aspiration levels involve three components of membership, non-membership, and indeterminacy. The membership function represents the satisfaction of each owner's optimistic profit goal. On the other hand, the non-membership function represents the dissatisfaction of the owner with the pessimistic profit share. The indeterminacy function represents hesitancy with higher profit levels due to product demand uncertainty. A case study composed of power generation, hydrogen production, and methanol production is used to illustrate the model. The case study results show that synergistic interaction between plants enables the allocation of a 127 % increase in profit margin for methanol production. A decrease of 24 % in CO_2 emissions is also observed from the case study.

1. Introduction

The development of new processes to convert low-value raw materials into high-value products is an important aspect of sustainable production. It enables lower negative environmental impacts and higher economic benefits. Process integration is a key method for establishing sustainable production by considering the interactions of components that make up a process network. One of the main developments in this area is the eco-industrial park (EIPs), which is a cluster of plants that exchange materials, utilities, and information to improve environmental performance and circularity (Aggeri, 2021). More than 245 EIPs exist worldwide as of 2021 (World Bank 2021). However, the interactions among participant companies in an EIP involve behavioural dimensions such as risk appetite. A systematic framework is needed to enable planning of EIPs considering risks and uncertainties.

Process systems engineering (PSE) tools have been developed for planning and designing EIPs (Boix et al., 2015). Ubando et al. (2015) developed a fuzzy mathematical programming model for the development of bioenergy parks. The model considers multiple conflicting objectives represented as fuzzy sets. Misrol et al. (2022) optimized the renewable energy allocation in an EIP using a mixed integer nonlinear program (MINLP). Networks for sharing utilities such as water play an important role in developing EIPs. A game-theoretic leader-follower approach was developed for the optimal design of EIP water networks (Aviso et al., 2010). Sa'ad et al. (2021) developed a non-linear programming (NLP) model for centralized water distribution in an EIP considering water reuse with single contaminant constraint. These tools provide a means for considering multiple conflicting

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interests in EIPs. However, none of these tools consider the complex nature of uncertainties that result from the varying risk appetites of different owners. In this study, an optimization model is developed to address this gap. This study develops a neutrosophic linear program (NeLP) for allocating economic benefits among the different participating plant owners in an EIP. Neutrosophic set theory is an extension of the classical fuzzy (Zadeh, 1965) and intuitionistic fuzzy (Atanassov, 1986) set theories for handling uncertainties. This concept, developed by Smarandache (2006), is comprised of membership, non-membership, and indeterminacy components. Decision tools involving neutrosophic sets have been applied recently to reduce agricultural carbon emissions (Zhang et al., 2025), to promote circular economy strategies (Kaviyarasu et al., 2024), and to implement sustainable waste valorization (Alqazzaz and Sallam, 2024). None of the past literature dealt with the planning and synthesis of EIPs considering the risk appetite of different participants. In this study, the components of neutrosophic sets are applied in the allocation of economic benefits generated by the EIP. The membership function represents the degree of satisfaction of the owner with higher economic benefits, while the non-membership represents the degree of dissatisfaction with lower economic benefits at a certain tolerance. The indeterminacy function represents how decision-makers are hesitant to increase the production level due to demand uncertainty or within a given tolerance. This concept can capture the risk behavior of the different owners in the EIP. The rest of the paper is organized as follows. Section 2 discusses the problem statement at which the model is based on. Section 3 contains the optimization model while Section 4 discusses a case study to illustrate the model. Section 5 synthesizes the results and discusses the conclusion and prospects for future work.

2. Problem statement

The formal problem statement for the development of the model is discussed as follows:

- The system consists of *m* streams from *n* operating units owned by *p* owners
- Each owner *k* manages a set of operating units that produces a certain set of products. It is assumed that these products are the main products of the operating units owned by owner *k*. It is also assumed that the costs of these units are attributed to the same owner.
- Each operating unit *j* can produce a certain flow rate of material or energy stream *i* at a fixed ratio. The cost of investing in these units is modelled as a linear function with fixed and variable costs.
- Each stream *i* can be sold or purchased at a fixed price and has a range of demand from a lower bound to an upper bound. Certain output streams involved in any unit are considered an emission stream with a lower bound of zero to a given upper bound.
- The symbiosis in the system by different owners is based on the profit allocation when all units are connected via a common stream. The profit allocation is based on the aspiration of each owner to make as much profit as possible. The neutrosophic nature of the profit allocation has three components. The membership function represents the degree of satisfaction with higher profit levels. The non-membership represents the dissatisfaction of the owners with lower profits, partially independent of that of the degree of satisfaction. The indeterminacy function represents hesitancy towards higher production with increasing profit due to uncertainty in the product demand.
- The model generates an optimal solution from the inputs of multiple decision makers. The tolerance levels of the non-membership and indeterminacy functions vary from one owner to another. The tolerance to dissatisfaction in the non-membership aspect represents the acceptability of lower profit levels while the tolerance to hesitancy in the indeterminacy aspects represents the risk tolerance of the owner to uncertainty in higher production levels. Both set the maximum degrees of dissatisfaction and indeterminacy, which can be set based on the model user's risk appetite.

3. Optimization model

The objective function of the model is to maximize the overall neutrosophic variable based on its three components:

$$\max \alpha - \beta - \gamma + \frac{1}{M}(W_P * PROF - W_E * EMISS) \tag{1}$$

subject to the following constraints:

$$PROF = HPY * \sum_i S_i x_i - AF * \sum_j (FC_j + VC_j x_j) \tag{2}$$

$$EMISS = \sum_m \sum_j A_{m,j} x_j \tag{3}$$

$$\left(P_k - P_k^{\mathrm{L}}\right) \geq \alpha\left(P_k^{\mathrm{U}} - P_k^{\mathrm{L}}\right) \qquad \forall k \in \mathcal{K} \tag{4}$$

$$\left(P_k^{\mathrm{U}} - P_k\right)(1 - TB_k) \le \beta\left(P_k^{\mathrm{U}} - P_k^{L}\right) \qquad \forall k \in \mathcal{K} \tag{5}$$

$$\left(P_k - P_k^{\mathrm{L}}\right)(1 - TG_k) \le \gamma\left(P_k^{\mathrm{U}} - P_k^{\mathrm{L}}\right) \qquad \forall k \in \mathcal{K} \tag{6}$$

$$\textstyle\sum_k P_k = PROF \tag{7}$$

$$PROF - PROF^{\mathrm{L}} \ge \alpha\left(PROF^{U} - PROF^{\mathrm{L}}\right) \tag{8}$$

$$\left(EMISS^{\mathrm{U}} - EMISS\right) \ge \alpha\left(EMISS^{\mathrm{U}} - EMISS^{\mathrm{L}}\right) \tag{9}$$

$$\textstyle\sum_i A_{i,j} x_j = y_i \qquad \forall i \in \mathcal{I} \tag{10}$$

$$Y_i^{L} \le y_i \le Y_i^{U} \qquad \forall i \in \mathcal{I} \tag{11}$$

$$0 \le \alpha \le 1; \qquad 0 \le \beta \le 1; \qquad 0 \le \gamma \le 1; \tag{12}$$

$$y_i \ge 0 \qquad \forall i \in \mathcal{I} \tag{13}$$

$$x_j \ge 0 \qquad \forall j \in \mathcal{J} \tag{14}$$

Eq(1) aggregates the components of the neutrosophic objectives of each plant owner in the system (i.e. maximizing overall satisfaction and minimizing both overall dissatisfaction and indeterminacy) with the fourth term of the objective function ensuring that the solution given is optimal with respect to the total annual profit (e.g. M USD/y) and emissions (e.g. Mt/y) of the system. The model considers the economic and environmental impacts of the system with W_P normalizes the profit and W_E normalizes the emissions. Eq(2) defines the total profit of the system which is based on the net revenue from the material and energy streams, the capital, and operation and maintenance costs of the processes. Eq(3) defines the net emissions from the system with the emission stream *m* as an element of the set of emissions $\mathcal{M} \subset \mathcal{I}$. Each owner *k* has an allocation of the total profit, PROF, that can be optimized based on the neutrosophic components of membership, non-membership, and indeterminacy as indicated in Eq(4) to Eq(6). The overall degree of satisfaction α, is the minimum degree of satisfaction of all owners' profit level, as well as that for the overall economic and environmental impact. On the other hand, the overall degrees of dissatisfaction, β, and hesitancy, γ, are the maximum degrees of dissatisfaction and hesitancy of all owner's profit level. The allocation of profit depends on the level of cooperation of each owner based on the TB_k, the tolerance towards lower profit levels. The parameter TG_k is the tolerance of the owners towards risks due to uncertainty of achieving the target profit at higher production levels. The allocated profit to each owner should sum up to the total profit of the system as defined in Eq(7). The fuzzy objectives of economic and environmental impacts are defined in Eq(8) and Eq(9), respectively. The input-output structure of the system is defined in Eq(10) and the final output of the streams is constrained between two values in Eq(11). The nature of the neutrosophic variables is defined in Eq(12) while the non-negative nature of the design variables is in Eq(13) and Eq(14). The resulting linear program (LP) is implemented in AIMMS 4.95 in a PC with 16.0 Gb of RAM and 2.90 GHz processor. Computational time is negligible for the case study to be implemented.

4. Case study

To illustrate the model, a case study is used involving three owners of three different processes. It consists of three plants: (1) power generation, (2) hydrogen production and (3) methanol production, independently owned by different owners. Table 1 shows the input-output structure of the three plants while Table 2 provides the final demand and selling prices of the products. The main products produced are electricity, H_2, and methanol, respectively. The data for the input and output structure of the system is based on the MIDDEN database (van Dam et al., 2021) while the data in Tables 2 and 3 are adapted and modified from Tapia (2021). Natural gas is the common raw material needed for all plants. The power generation plant is supplying the utilities to the H_2 production and the methanol plant. The H_2 production plant supplies the hydrogen needed by the methanol plant. The annualizing factor is 0.10 /y while the annual operating hours are 8,000 h/y. In Table 2, the upper bound of the CO_2 emission is set when the system is optimized for maximum profit subject to the demand bounds. It is then reduced for a scenario that 20 % reduction is needed. The CO_2 emissions have an upper bound of 326.41 Mt/y if no reduction target is set and 261.12 Mt/y for a minimum of 20 % reduction target.

Table 1: Input and output ratios of the streams involved in the case study (van Dam et al., 2021)

Stream	Power Generation	H_2 Production	Methanol Production
Natural Gas, GJ/h	-4.5	-182	-32.7
Electricity, GJ/h	1	-0.48	-0.13
Steam, GJ/h	1.9	-18.48	-3.1896
Methanol, t/h	0	0	1
H_2, t/h	0	1	-0.03
CO_2, t/h	0.2475	9	0.48

Table 2: Selling prices and demand bounds of the streams involved in the case study (Tapia, 2021)

Stream	Selling Price	Minimum Output	Maximum Output
Natural Gas	8.333 USD/GJ	-	0
Electricity	30 USD/GJ	360 GJ/h	1,260 GJ/h
Steam	30 USD/GJ	900 GJ/h	1,440 GJ/h
Methanol	520 USD/t	8 t/h	20 GJ/h
H_2	4,000 USD/t	3 t/h	10 GJ/h
CO_2	-	-	326.405 (no reduction) 261.12 (20 % reduction)

Table 3: Cost data of the processes involved in the system in the case study (Tapia, 2021)

Process	Main Product, unit	Fixed Cost (USD)	Variable Cost (USD per capacity)
Power Generation	Electricity, GJ/h	459,000	1,138,000
H_2 Production	H_2, GJ/h	37,000,000	180.57
Methanol Production	Methanol, t/h	5,000,000	100,000

The profit bounds for all processes are determined based on maximizing the individual profit if all processes are independently operating. However, a discounted selling price is set for a certain stream that comes from one plant in the system supplied to another. For instance, the hydrogen needed for methanol production is sold at a lower price to the owner of the methanol plant compared to when it is sold externally. Table 4 summarizes the selling price set. The external prices defined below are based on the prices set by the owner for their main product (i.e. electricity and steam for Owner 1, hydrogen for Owner 2, and methanol for Owner 3).

Table 4: Selling prices set for each owner in the system

Stream	Owner 1 Price	Owner 2 Price	Owner 3 Price	External Price
Natural Gas	8.333 USD/GJ	8.333 USD/GJ	8.333 USD/GJ	8.333 USD/GJ
Electricity	30 USD/GJ	25 USD/GJ	25 USD/GJ	30 USD/GJ
Steam	30 USD/GJ	25 USD/GJ	25 USD/GJ	30 USD/GJ
Methanol	-	-	520 USD/t	520 USD/t
H_2	-	4,000 USD/t	3,000 USD/t	4,000 USD/t

The bounds for the profit solved and the tolerance values for all owners in this case study are given in Table 5. The lower bound of the profit can be determined by getting the minimum profit for each owner while satisfying the required demand and setting an arbitrary 50 % margin. The upper bound of the profit can be determined by maximizing the total profit for each owner. The tolerance levels are set higher for power generation process as it has a higher profit margin among the three processes. On the other hand, the owners of the hydrogen and methanol plants are set to have a completely neutrosophic risk appetite where the degree of dissatisfaction and hesitancy are set to be at the maximum. The lower bound for the total profit is at 290.17 M USD/y and an upper bound of 430.33 M USD/y.

Table 5: Profit bounds and risk tolerance levels for each owner

Owner	Process Owned	Lower Bound (M USD/y)	Upper Bound (M USD/y)	Dissatisfaction Tolerance, TB_k	Indeterminacy Tolerance, TG_k
1	Power Generation	219.47	252.42	0.8	0.8
2	H_2 Production	68.89	166.69	0	0
3	Methanol Production	1.81	11.22	0	0

Solving the model given by Eq(1) subject to constraints in Eq(2) to Eq(14), results in the optimal process presented in Figure 1 while the optimal profit allocation is given in Table 6 for two different risk tolerance settings. The total profit of the system is equal to 324.86 M USD/y. The steam output is close to the minimum demand while the methanol output is equal to the minimum. The hydrogen output is maximized at 10 t/h. For the given risk tolerance values in Table 5, the economic benefits are divided to allocate 70 % for power generation, 29 % for H_2 production and 1 % for methanol production. The total CO_2 emission is 245.59 Mt/y, which indicates a 24.7 % reduction in emissions compared to the maximum economic benefit possible. If the maximum CO_2 emissions is set to have at least 20 % reduction, the total emissions become 232.24 Mt/y, which indicates a 28.8 % reduction. The dissatisfaction and indeterminacy risk tolerance levels of different owners affect the allocation. Considering the baseline risk tolerances values in Table 5, a higher allocation is given to power generation to provide margins from the minimum profit. Considering that all plants have maximum tolerance to indeterminacy, i.e., TG_k=1, then the total profit is at the maximum. Here, a higher allocation is given to the methanol plant to drive its profit margin close to the maximum. This insight allows the synergistic interaction between process plants to meet their profit margins. The resulting optimal solution may be used to systematically allocate the profit to manage risk in forming industrial symbiosis.

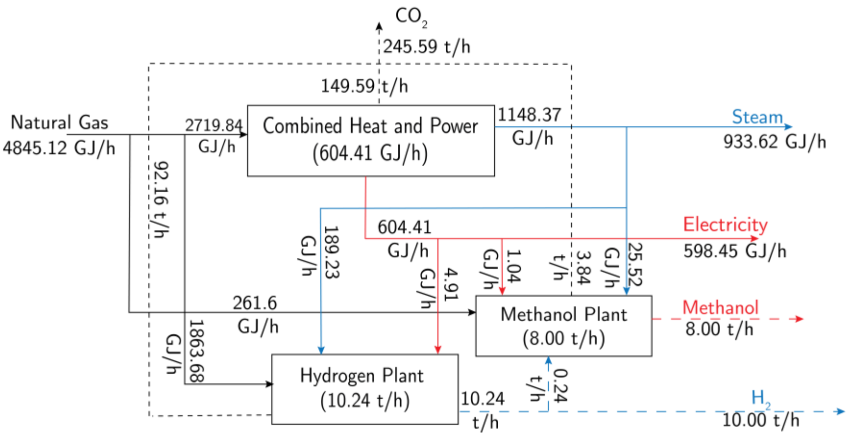

Figure 1: Optimal input and output flows for the case study

Table 6: Optimal profit allocation for the case study.

Owner	Process Owned	Optimal Profit (M USD/y)	Optimal Profit (M USD/y) For TB_k=0 and TG_k=0	Optimal Profit (M USD/y) For TB_k=0 and TG_k=1
1	Power Generation	227.62	227.62	248.76
2	H_2 Production	93.10	93.10	155.88
3	Methanol Production	4.14	4.14	10.18

The synergistic interaction between processes with different owners is exhibited in this case study. In Figure 1, 19 % of the steam generated from power generation is allocated to the hydrogen and methanol plants, enabling them to satisfy the maximum demand for both production plants. Considering that the stream is supplied with a net profit of zero for internal streams, the symbiosis between three plants enables the increase of profit for the methanol plant from 1.8 M USD/y to 4.14 M USD/y based on the solution of the neutrosophic linear program. The high tolerance of the power generation plant also contributes to this allocation. The model has generated important insights on the allocation of economic benefits to different plant owners based on their risk appetite under neutrosophic decision environment. It also generates useful insights on setting final demand output to attain reasonable CO_2 emissions reduction.

5. Conclusion

A neutrosophic linear program was developed to allocate economic benefits to different process plants in industrial symbiosis. The model can determine the optimal size of these power plants subject to the demand constraint and risk appetite of the decision-makers in the system. The neutrosophic nature of the model incorporates the degree of satisfaction with higher profit, degree of dissatisfaction with lower profit, and degree of hesitancy due to uncertainty in product demand. The risk appetites of the decision makers can be modelled as tolerances to dissatisfaction and indeterminacy. From the case study used as illustration, these tolerances enable the allocation of lower level of profit to owners with higher tolerance. The result of the case study provides insights into the allocation of the profit of the whole system when all the processes interact as one industrial park. Future work should include extending the model to incorporate units co-owned by two owners. Cooperative game theory concepts can also be integrated into the model.

Nomenclature

AF – annualizing factor
A_{ij} – technical coefficient of stream *i* in process *j*
A_{mj} – technical coefficient of emission *m* in process *j*
EMISS – total annual emissions
$EMISS^L$ – lower bound of total annual emissions
$EMISS^U$ – upper bound of total annual emissions
FC_j – fixed cost of process *j*
HPY – operating hours per year
PROF – total annual profit
$PROF^L$ – lower bound of total annual profit
$PROF^U$ – upper bound of total annual profit
P_k – total annual profit allocated to owner *k*
$P^L{}_k$ – lower bound of profit for owner *k*
$P^U{}_k$ – upper bound of profit for owner *k*
S_i – selling price of product *i*
TB_k – risk tolerance parameter to dissatisfaction
TG_k – risk tolerance parameter to indeterminacy
VC_j – variable cost of process *j*
W_E – normalization factor for emissions
W_P – normalization factor for profit
x_j – scaling factor of process *j*
y_i – final output of product *i*
$Y^L{}_i$ – lower bound for the final output of product *i*
$Y^L{}_i$ – upper bound for the final output of product *i*
α – overall degree of satisfaction
β – overall degree of dissatisfaction
γ – overall degree of hesitancy

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