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Integrated Evaluation Framework of the Cogeneration Energy System via Application of Fuzzy P-graph

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Process Integration via the cogeneration energy system is widely utilised for its ability to generate both electricity and usable heat simultaneously. However, the decision to integrate a cogeneration energy system in an energy portfolio requires a synchronous analysis of multiple objectives. Previous work in the field introduced a novel fuzzy P-graph approach for the optimal synthesis of cogeneration and polygeneration systems. In this paper, an integrated evaluation framework using the fuzzy P-graph has been proposed. The conflicting objectives are introduced as indicators in the modelling framework for targeting purposes. The acceptable range of the said objectives is transformed into fuzzy limits. A case study from previous work is adapted to evince the potential of the developed model. The result shows that both demand and cost indicators can be targeted at the same time, allowing the multi-objective decision-making problem in the energy system design to be tackled effectively.

1. Introduction

The world today is faced with an energy trilemma, where it is necessary to promise energy security (supply and demand), environmental sustainability, and energy equity (cost) in power generation (World Energy Council, 2019). A considerable portion of global carbon emission is associated with the energy generation capacities (Dong et al., 2019) as they are responsible for the extensive use of energy resources. To tackle the conundrum at its core, the energy system design must be reinvented. Process Integration (PI) techniques which emphasise holistic system design have been the centre of focus for many researchers in recent years. The cogeneration energy system, which can concurrently produce useful heat energy and electricity, is one great example. The exploitation of initially underutilised energies and processes via Pinch Analysis (PA), Mathematical Programming (MP), or the graph-theoretical P-graph can maximise the ability to achieve simultaneous goals as in the trilemma (Klemeš and Varbanov, 2015). For instance, Abdul Aziz et al. (2017) applied an integrated PA framework in an industrial site planning, Wang et al. (2019) proposed a novel optimisation design for integrated energy system via MP, while Lim et al. (2020) have utilised P-graph to plan the hydrogen energy network.
When designing an optimal cogeneration energy system, the existence of contradictory objectives will cause the policymakers to have trouble deciding between equally preferable goals, *Sophie's Choice* (Styron, 1979). Finding the optimal design is a multi-objective decision making (MODM) problem that requires the consideration of all plausible alternatives and criteria (Kumar et al., 2020). The graph-theoretic P-graph is deemed better at suggesting optimal solutions as it could represent realistic Process Network Synthesis (PNS) problem, propose all optimal and near-optimal solutions, and provide intuitive insights through mathematically-rigorous heuristic algorithms (Klemeš and Varbanov, 2015). The framework itself was first proposed by Friedler et al. (1992a) to address the complex and combinatorial PNS problem. In P-graph, combinatorial algorithms are applied to inspect all optimal and near-optimal solutions in an accelerated manner. While optimal solutions are often prioritised, the generated subpar solutions are feasible in real-life energy system synthesis (Voll et al., 2015). As a graphically based optimisation tool, P-graph has proven successful in many areas and received many enhancements throughout the years. Notably, a recent paper by Aviso and Tan (2017) has utilised P-graph to

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introduce the ability to model fuzziness in the design of the energy system – which allows the representation of uncertainties or interval constraints.
The optimal design of the cogeneration energy system needs a comprehensive analysis of all available options and their contributions towards achieving the objectives. From the review of previous works, it is observed that there has been a lack of studies done in an integrated manner. The configuration for the energy system is solely designed towards satisfying demands, while the economic and environmental metrics are calculated after. In some papers, targeting in P-graph were attempted, such as the integration of the 'cost' and 'sustainability' indicators by Cabezas et al. (2015) and the introduction of the 'Greenhouse gases (GHG) avoided' metric by Fan et al. (2020). However, they only act as accounting tools to find out the involved amount.
This paper intends to integrate multiple indicators and showcase the pioneering application of fuzzy P-graph in holistic energy planning. All the viable criteria and objectives towards the design are represented in the model. The deterministic indicators are first transformed into fuzzy limits; then, the fuzzy P-graph is used to target their membership satisfaction. A hypothetical case study adapted from existing work is used. Using the fuzzy P-graph model, the fulfilment of the energy system's demands is maximised while the costs are minimised systematically. The postulated integrated framework signifies the plausibility of the fuzzy P-graph in comprehensive planning.

2. Methodology

This section presents the derivation of the integrated evaluation framework from the concept of fuzzy P-graph and the targeting of cost and sustainability aspects in an energy system. To allow a more holistic energy system planning, this paper proposes an integrated evaluation framework by adopting the simultaneous targeting elements into the fuzzy P-graph.

2.1 Fuzzy P-graph framework

A P-graph or process graph is a type of bipartite graph that resembles the arrangement of a PNS system. It uses an M-type node (circular nodes) to represent the material streams and an O-type node (horizontal bars) to depict the operating units. Both nodes will then be connected to reflect the inputs and outputs of a process. Given its unique node-connecting features, P-graph has been implemented in many PNS or PNS-like problems. Klemeš and Varbanov (2015) have published a critical review on the latest applications of the efficient P-graph framework in many combinatorial PNS problems, while the work authored by Friedler et al. (2019) has subsequently detailed the directions for further development of the framework. In P-graph, an axiom system with five propositions has been established to ensure a combinatorially feasible structure could be obtained. The fundamentals of the axiom system are detailed in the work by Friedler et al. (1992b). In solving the constructed model in P-graph, the framework makes use of three algorithms to generate the optimal and near-optimal solutions based on the specified objective function. Maximal Structure Generation (MSG) yields the simplest or maximal superstructure, which is mathematically rigorous. Solution Structure Generation (SSG) generates all solution structures from the maximal structure. Accelerated Branch and Bound (ABB) efficiently searches the optimal and near-optimal solutions (Friedler et al., 1996).
The P-graph framework is widely used in optimising both the cost and sustainability aspects of an energy system. Through the incorporation of indicators as raw materials, the allocation of required or maximum value can be transformed to target the relevant objectives (Cabezas et al., 2015). Figure 1a below demonstrates the proposed structure to optimise both 'cost' and 'sustainability' indicators in P-graph.

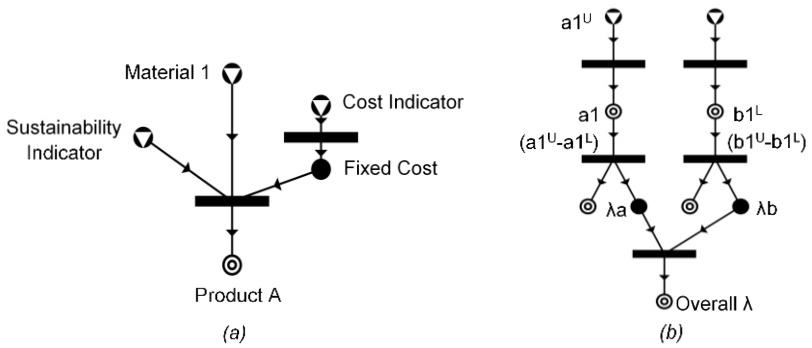

Figure 1: Representation of (a) optimisation of sustainability and cost indicators (adapted from Cabezas et al., 2015) and (b) fuzzy P-graph with minimisation of fuzzy 'a' constraint and maximisation of fuzzy 'b' constraint (adapted from Aviso and Tan, 2018)

P-graph is often used in the case where deterministic constraints are specified using an interval-based input. However, Aviso and Tan (2017) have successfully extended this limitation by introducing fictitious operating units to represent the postulation of membership satisfaction for fuzzy constraints. Fuzzy set theory has been propounded to model the uncertainties by Zadeh (1965), and Zimmermann (1978) was the first to propose fuzzy linear programming. Fuzzy P-graph is the application of the said fuzzy optimisation within the P-graph framework. Detailed elaboration and formulation on the inner workings for fuzzy P-graph can be found in the work by Aviso and Tan (2018), and Figure 1b shows the postulated representation.

2.2 Integrated evaluation framework using fuzzy P-graph

The fuzzy P-graph introduced by Aviso and Tan (2017) and simultaneous targeting proposed by Cabezas et al. (2015) laid the primary groundwork for the basis of this paper. By merging the structure in both Figures 1 and 2, it is proposed that the targeting of other indicators (apart from the system's demand fulfilment) is doable. Integrated evaluation and simultaneous analysis of several indicators can be done inside the P-graph framework and make use of the mathematically rigorous P-graph algorithms. The developed integrated evaluation framework involving two constraints is shown in Figure 2 below. The constraints are adapted into fuzzy limits to ensure targeting can be done.

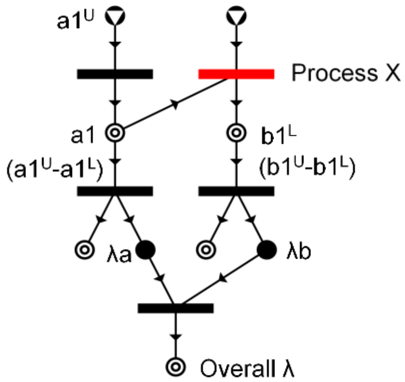

Figure 2: Integrated Evaluation Framework for minimisation of fuzzy 'a' constraint and maximisation of fuzzy 'b' constraint

Assuming process X exists, it will consume the raw materials to generate the desired products. Figure 3 shows there are two types of raw materials – 'a', which needs to be minimised, and 'b', which should be maximised. For the minimisation of 'a' constraint, the upper limit must be specified as well as the acceptable values for the least and most satisfying scenarios. Some examples for 'a' are the constraints that usually have an upper limit and thrive on being minimised, such as 'cost' and 'sustainability' indicators. As for 'b' constraint, the lower limit and acceptable range between the minimum and maximum must be inputted. The constraint for 'b', which has an absolute minimum and preferably maximised is the 'demand' indicator. The concept of fuzzy limits is used to define the acceptable range for the constraints, allowing membership satisfaction to be evaluated holistically.

In this paper, the functionality of the integrated evaluation framework was demonstrated by the simultaneous targeting of both 'cost' and 'demand' indicators. Before specifying the upper or lower limit of a constraint, it is crucial to identify the baseline value to ensure that the designated fuzzy limits are reasonable and practical. For instance, for the 'cost' indicator, which thrives on being minimised, its baseline value should be calculated manually or by the incorporation of 'cost' as the raw material in the P-graph model. After that, the decision-maker(s) can proceed to decide the minimum (least satisfied) and maximum (most satisfied) target and input them accordingly to the fuzzy P-graph as the upper limit and fuzzy range. Similarly, for the 'demand' indicator, which should be maximised, the lower limit and desirable fuzzy range must be identified before being modelled in the fuzzy P-graph. In the next section, a simple case study on the design of a cogeneration system is considered to exhibit the working of the comprehensive evaluation model. The model will demonstrate the targeting and transformation of constraints into fuzzy limits.

3. Case study

In this paper, the case study data in the fuzzy P-graph by Aviso and Tan (2018) would be adapted. The formal problem statement is to design a cogeneration system given N number of available technologies to produce M number of product streams to fulfil the fuzzy demands simultaneously. In this problem, the available technologies which use natural gas as fuel are (1) combined heat and power (CHP) unit, (2) boiler, (3) hot water generator (HWG), and (4) steam-water heat exchanger (HE). At the same time, the products required are (a) electricity, (b) steam at 1.2 bar, and (c) hot water at 70 °C. The process matrix, fuzzy limits, and associated economic data adapted from Sy et al. (2018) are summarised in Table 1. A negative entry means that the said material is consumed in the process, while a positive value signifies the generation of the product.

Table 1: Data for the design of an optimal cogeneration system (adapted from Sy et al., 2018)

	CHP	Boiler	HWG	HE	$Y(y^L – y^U)$	Price (€/MWh)
Natural Gas (MW)	-4.06	-1.20	-1.08	0	-	20
Electricity (MW)	1.00	0	0	0	10 – 15	90
Steam (MW)	1.83	1.00	0	-1.00	20 – 24	40
Hot Water (MW)	0.53	0	1.00	1.00	6 – 9	30
Fixed Cost (€)	382,500	45,500	7,500	625	-	-
Variable Cost (€/MW)	948,347	175,000	39,474	4,688	-	-

3.1 Integrated cost accounting

In the previous paper, the feasible solution structures are first obtained – then the annual profit is calculated manually, using the following Eq(1) adapted from the work by Aviso and Tan (2018). AP represents the annual profit, AWH represents the annual working hours of 8,000 h, AF signifies the annualising factor of 0.1, y_i represents the flowrate for material stream i and b_j is a binary variable which indicates selection of process unit j and x_j signifies capacity. Lastly, FC_j and VC_j are the fixed cost and variable cost.

$$AP = AWH * \sum_{i=1}^{s} y_i c_i + AF\left(\sum_{j=1}^{n} (b_j FC_j + x_j VC_j)\right) \quad (1)$$

To display the capability of this framework in cost accounting, the cost indicators: (A) ‘Fixed Cost’, (B) ‘Variable Cost’, and (C) ‘Utility Cost’ are introduced into the model. The P-graph representation of the simultaneous cost and demand targeting is the same as the representation shown in Figure 3. It is important to note that the three indicators are derived from the Eq(1) above, where ‘Fixed Cost’ and ‘Variable Cost’ are necessarily segregated in the second half for the equation while ‘Utility Cost’ comes from the first half.
The solution given in Table 2 selects the same structure as in the previous work by Aviso and Tan (2018). By the inclusion of new indicators, the cost result can be obtained inside the P-graph concurrently. Note that both ‘Fixed Cost’ and ‘Variable Cost’ have a negative value, which means they incur expenditures for the system. At the same time, ‘Utility Cost’ is bringing in the profit.

Table 2: Resulting parameters for the optimal configuration (overall λ = 0.80)

Process Units	Capacity (MW)	Streams	Flowrate (MWh)	Types of Cost	Amount (€)
CHP	13.98	Natural Gas	-56.77	Fixed	-38,312.50
Boiler	0.00	Electricity	13.98	Variable	-1,326,820
HWG	0.00	Steam	24.00	Utility	10,824,400
HE	1.59	Hot Water	9.00		
				Total	9,459,267.50

The optimal solution structure chooses CHP and HE to fulfil the identified demand given in Table 1. The capacity obtained suggests the optimal sizing for the process units in the energy system. Both the CHP and HE should be sized at 13.98 MW and 1.59 MW to meet the maximum demand requirements for steam and hot water, while electricity achieves 13.98 MWh, which leads to an overall λ of 0.80. An annual profit of 9.459 M€ is obtained, which has a negligible deviation (< 0.02 %) as compared to the 9.457 M€ in the previous work. Primarily, this demonstration of the evaluation model offers a new alternative for researchers to carry out a similar accounting function via the introduction of new indicators. Meaningful targeting can be done where decision-maker(s) can define the preferable range for the value of the said indicators.

3.2 Simultaneous cost and demand targeting

Using the developed model, it is possible to set the ceiling value for the ‘Fixed Cost’, ‘Variable Cost’, and ‘Utility Cost’ to target the initial investment amount, monthly cash flow, or intended profit of the system itself. This further allows a synchronous cost and demand targeting in designing the energy system. In cases where there might be a minimum and maximum target, fuzzy limits can be utilised to convey the degree of satisfaction for the said constraints. As an example, the ‘Variable Cost’ is set to have a maximum of € 1,200,000 and a preferable minimum (λ = 1) at € 1,100,000 in the following case study. Figure 4 shows the integrated P-graph evaluation model after simultaneous targeting. From the optimisation, the overall satisfaction is given as 0.44. The result is tabulated in Table 3 below. Do note that the greyed-out operating unit, boiler, is not selected.

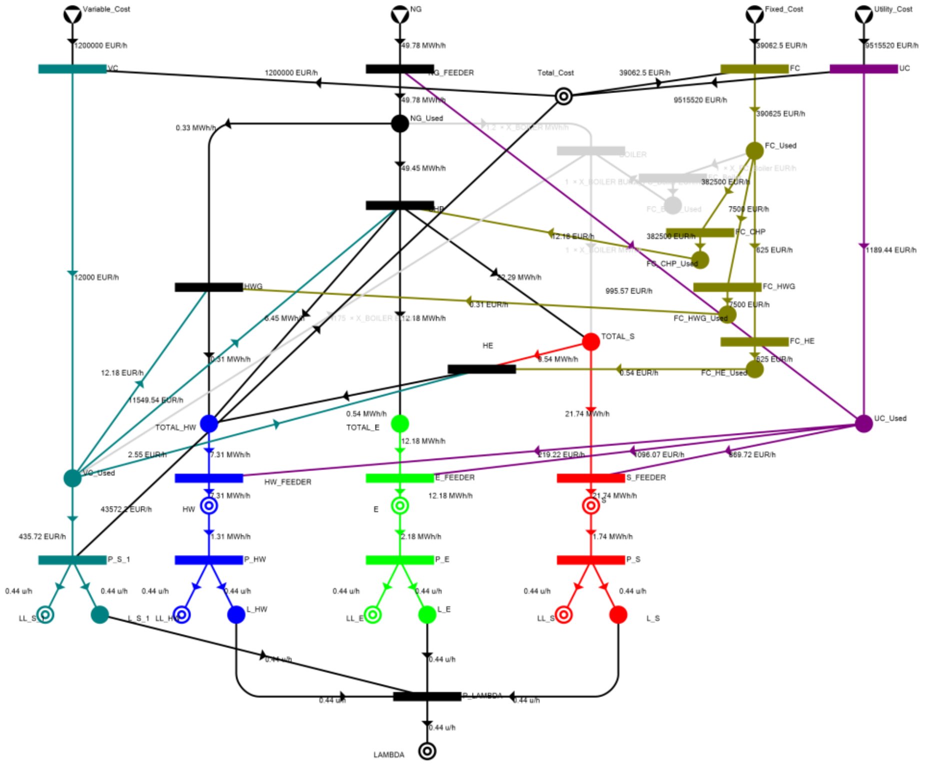

Figure 4: Representation of Integrated Evaluation Framework in the cogeneration energy system planning

Table 3: Resulting parameters for the optimal configuration with ‘Variable Cost’ targeting (overall λ = 0.44)

Process Units	Capacity (MW)	Streams	Flowrate (MWh)	Types of Cost	Amount (€)
CHP	12.18	Natural Gas	-49.78	Fixed	-39,062.5
Boiler	0.00	Electricity	12.18	Variable	-1,156,427.80
HWG	0.31	Steam	21.74	Utility	9,515,500
HE	0.54	Hot Water	7.31		
				Total	8,320,009.70

Apart from the most-optimised solution, the evaluation model can generate other plausible solutions which might be practical in other settings despite the lower overall satisfaction value. The solution structure, which ranked second, has an overall λ of 0.43 and chooses CHP and HWG of different capacities to suit the model’s inputted requirements. The alternatives can be useful for system planners to analyse different options. The conceptual idea of introducing additional discrete indicators into the evaluation framework can allow the decision-makers to carry out a holistic and integrated analysis.

4. Conclusion

A fuzzy P-graph evaluation framework that allows the simultaneous targeting of both demand and cost indicators has been proposed in this paper. The developed model is utilised in the case study to design the optimal cogeneration energy system. The results of the optimal design of the energy system show that CHP is the preferable choice because it can generate more electricity and heat using less fuel – effectively lowering its cost and environmental footprint. By applying the integrated evaluation framework, a holistic energy planning can be done to decide the optimal mix for the power-generating technologies by simultaneous evaluating the demand’s fulfilment, cost, and sustainability indicators. The framework can be adapted to solve other MODM problems, and the presented case study merely shows one of the possible applications.

This work, however, has only addressed indicators which have a linear capital-cost function. Non-linear functions can be attempted to be integrated into the model to tackle non-linearity in complex problems. For the integration of indicators, the extension to include sustainability indicators such as Carbon Footprint (CFP), Water Footprint (WFP), and Land Footprint (LFP) can create a more comprehensive assessment. Future research can also explore more on the multi-objective aspect and weighting in P-graph to tackle other MODM problems. Exploration of arithmetic operation for the fuzzy number could also be considered for future study.

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