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Optimal Fertigation for Automated Fertilizer Blending System by Minimising Fertilizer Cost and Utility Consumption

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In agricultural industries, efficient nutrient and water management are crucial to saving costs maximising crop yields, and increasing profit. A fertigation system is used to irrigate sufficient nutrients and water for the growing needs of the crops. However, the water and nutrient volume needed for each crop remains unknown due to various crop phases and the dynamics of nutritional demand. Therefore, this research work presents the optimisation modeling for an Automated Fertilizer Blending System (AFBS) to minimise the operational cost of nutrients, water, and electricity. The proposed optimisation model considers for the AFBS: (i) operational status of irrigation pump and stock tanks; (ii) stocks level for nutrient and water at each stock tank; (iii) inventory level for nutrient solutions in an AFBS tank; and (iv) nutrient and water level of the plants. The mathematical model is developed as mixed-integer linear programming (MILP). The optimisation problem is modeled using GAMS v-38.2.1 and solved by CPLEX 12 with a zero-optimality gap. In conclusion, cost comparison analysis between electricity, fertilizer, and supplied water represents the optimal cost percentage in engaging with nutrient losses minimised by 30%, water runoff, and electricity costs for optimal condition-based fertigation systems.

1. Introduction

The mismanagement of adding fertilizers and water to crops negatively impacts the sustainability of the planet, people, and profits. Nitrogen (N), Phosphorus (P), and Potassium (K) are the main nutrients in fertilizers, and they are absorbed into crops along with water. Poor management of nutrients (especially nitrogen) and water runoff has led to soil degradation and water pollution known as eutrophication. As reported by Chang et al. (2021), nitrogen input is critical for agricultural production, and this excess nitrogen can lead to severe ecosystem damage and water pollution.
Finally, due to the different growth stages of plants requiring different amounts of nutrients and this issue is still unknown. Therefore, without knowing the actual needs of plants, the amount of water and nutrients supplied to plants will affect the growth of plants and cause high costs to the agro-industry. Therefore, efficient management of fertilizers and water is critical to saving costs, producing high-quality crops, and maximising crop yields.
According to Razak et al. (2021), the best strategy to reduce this complexity is to adapt and adopt computer-aided model-based product design. The strategy to reduce this complex effect due to the agriculture industry is by constructing an effective schedule for fertigation using mathematical optimisation. This is to maximise the absorption of nutrients and water supply given to the crops and to support the crop development at an accurate level and period. The key decisions to be made by the optimisation model are:

i. The operational status (e.g. On and Off) of irrigation pumps and stock tanks.
ii. Inventory level for blending and each stock tank (fertilizer and water).
iii. Nutrient and water levels are needed by the plants.

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1.1 Optimisation model of fertigation

Fertigation is extensively used as a dispenser unit for agriculture industry use, making it more accessible and comfortable in general landscaping systems. Dosing device for standard results, where nutrients are introduced and good irrigation is needed for fertigation (Draman et al., 2021). Zulkafli and Kopanos (2018) explained that the proposed optimisation framework can be used to integrate different types of material and energy supply chain operations using a unified model representation to manage this interdependent network more efficiently, both techno-economically and environmentally. This fertigation system also minimised crop fertilizer uses by 30% (Aziz et al., 2021).
In the previous study, Kandelous et al. (2012) presented a design for optimal subsurface drip irrigation systems using optimisation model AMALGAM to estimate the cost-saving using cost-benefit analysis. Furthermore, minimising fertilizer is a much-needed optimisation technique that has a major impact on healthy crops and sustainable agricultural practices (Amudha et al., 2021).

1.2 Significance of the study

Although there is a large body of work in the open literature involving different methods of optimising fertigation, there is a lack of a unified model representation that addresses nutrient excess, water runoff, and costs in an integrated optimisation framework. Therefore, the novelty of this study is to optimise fertigation by using a Mixed Integer Linear Programming (MILP) optimisation model to create an efficient fertigation schedule to reduce operating costs, avoid overuse of fertilizers/nutrients, and avoid adverse effects on the environment. The optimisation model is written in GAMS v-38.2.1, and solved by CPLEX 12. This research work highlights a predicted and prescriptive analysis of an optimisation modeling of the Automated Fertilizer Blending System (AFBS) as one of the best available techniques (BAT) to minimise the cost of fertilizer, water, and electricity compared to the trial-and-error experimental works.

2. Methodology and Materials

2.1 Systematic Methodology

This research aims to formulate a mathematical optimisation model to reduce the cost due to nutrient losses and excess utility consumption (e.g. water and electricity). This systematic methodological framework had been adopted by (Razak et al., 2021) for blending, fertilizer formulation (Nor et al., 2018), optimum irrigation system (Draman et al., 2021), and operational planning of utility and production systems (Zulkafli and Kopanos 2016).
Limited research and attention are given in the literature on the decision to reduce nitrate leaching by applying the exactly amount of fertilizer and water required by the crop. According to author's best knowledge, limited study in the literatures that address the optimal cost of fertilizer, water, and electricity in an optimisation model. This work addresses the research gap on the modelling of fertigation system for AFBS. Therefore, the main novelty of this work is the new optimisation model framework for determining optimal fertilizer and utility costs considering nutrient and water requirements. Based on Kroggel M. and Kubota C. (2018) the cost percentage of fertilizer usage in time-based fertigation for 80 days tomato plant growth was higher compared to optimal condition-based fertigation as shown in Figure 1.

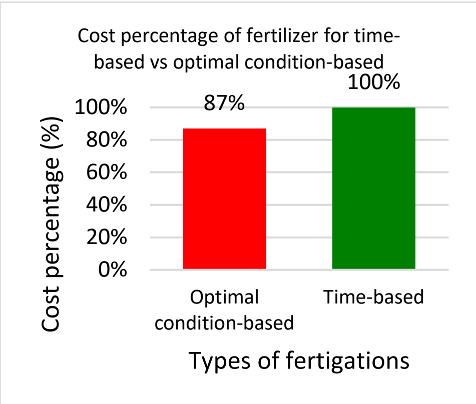

Figure 1: Comparison of fertilizer cost percentage of time-based and optimal condition-based in agriculture.

The four systematic stepwise optimal fertigations for automated fertilizer blending systems are cordially outlined in Figure 2. The input parameters are minimum or maximum fertilizer level, water and nutrient demand, the volume of blending and stock tank, electricity price, water, nutrient, and penalty cost.

Task 1 is problem definition which consists of three parts defining the variables (Task 1.1), target properties (Task 1.2), and constraints (Task 1.3). The target properties are nutrient and utility costs. The continuous and binary variables are blending outlet, blending inlet, fertilizer outlet, fertilizer inlet, water inlet, water outlet, nutrient absorbed, nutrient level, nutrient supply, and total cost. The constraints are tabulated in Table 1. The constraints as mentioned by Zulkafli and Kopanos (2016) set a limit related to the fertilizer quantity, nutrients for plants, lower and upper bounds for the flow of nutrients to plants, nutrient balance for each plant, the lower and upper boundary for nutrient contents, the demand of nutrients; and the objective function. Task 2 is property model identification to predict nutrient blend and utility consumption properties. In this task, the attributes of the variable are converted to upper and lower bounds of nutrient contents.

Task 3 is the generation of optimum nutrient blends and utility consumption candidates consisting of three parts declaring and defining data (Task 3.1), coding the optimisation model in GAMS (Task 3.2), and optimal operational cost (Task 3.3). According to Mahmud et al., (2018), GAMS is a high-level modeling system for mathematical optimisation. It is designed for modeling and solving different types of problems - linear, nonlinear, and mixed-integer optimisation problems. The main feature of this program is also that it can be used on different computer platforms, and the models can be ported from one platform to another. Mathematical models are plugged into the software environment to be solved using the appropriate programming language to produce results. All variables and other basic information must also be written entirely in the programming language.

Task 4 is cost-benefits analysis (CBA). A CBA is a process of comparing the projected or estimated costs and benefits associated with a project decision to determine whether it makes sense from a business perspective (Tim Stobierski, 2019).

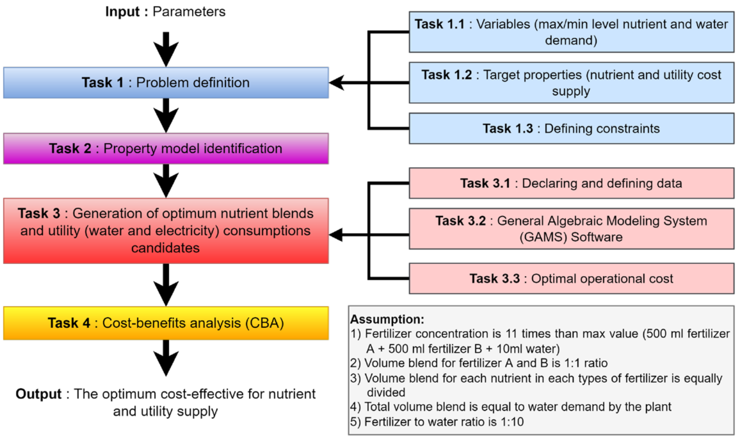

Figure 2: Systematic methodology of optimal fertigation for automated fertilizer blending system.

2.2 Development of optimisation systematic framework of fertigation

2.2.1 Constraints and parameters

The optimisation problem is modelled as mixed-integer linear programming (MILP). As shown in Table 1, continuous constraints are set based on the lower and upper bounds of each target attribute. Fertilizer blend for target attribute models, constraints, and target values encoded in GAMS. Two binary variables are known as $X_{(t)}$ if the pump is used and $Y_{(t)}$ if the stock tank is used in the respective period. All capital letters represent variables and Greek letters represent parameters of the optimisation framework.

2.2.2 Objective function

The objective function of this optimisation framework model has been successfully achieved by satisfying all constraints. The objective function is to minimise the operational cost of fertigation, as in Equation (1):

$$\min\left[\sum_{(t)} \emptyset_t^{elec} X_{(t)} + \sum_{(j,t)} \emptyset_{(j)}^{fertilizer} FI_{(j,t)} + \sum_{(q,t)} \emptyset_{(q)}^{water} WI_{(q,t)} + \sum_{(i,n,t)} \emptyset_{(t)}^{penalty} U_{(i,n,t)} + \sum_{(q,t)} \emptyset_{(t)}^{penalty} UW_{(q,t)}\right] \quad (1)$$

The optimisation model consists of irrigation electricity cost, $\emptyset_t^{elec}$, fertilizer cost, $\emptyset_{(j)}^{fertilizer}$ and supplied water cost, $\emptyset_{(q)}^{water}$. $\emptyset_n^{penalty}$ is the penalty cost that must be imposed to avoid additional purchases of fertilizer and water. The electricity prices are referred for low voltage agriculture tariffs from Tenaga Nasional Berhad (TNB)

Malaysia. The water cost is an industrial water tariff and the fertilizer cost is calculated based on the standard price of 1 kg basic for each nutrient.

Table 1: Target attributes models and constraints

Attributes	Constraints	Equation	Initial parameter	Lower bound	Upper bound	Reference
Fertilizer	Level of fertilizer, $F_{(j,t)}$	$F_{(j,t)} = \tilde{\alpha}_{(j)} + FI_{(j,t)} - FO_{(j,t)}$, $\forall j \in J, t \in T: t = 1$ $F_{(j,t)} = F_{(j,t-1)} + FI_{(j,t)} - FO_{(j,t)} \quad \forall j \in J, t \in T: t > 1$	$\tilde{\alpha}_{(j)}$	0.2	32	(Zulkafli and Kopanos, 2016)
	Fertilizer outlet $FO_{(j,t)}$ with pump $Y_{(t)}$	$\delta_{(j,t)}^{min} Y_{(t)} \leq FO_{(j,t)} \leq \delta_{(j,t)}^{max} Y_{(t)} \quad \forall j \in J, t \in T$		0.3	5.39	
Water	Water level in stock tank, $W_{(q,t)}$	$W_{(q,t)} = \tilde{\varepsilon}_{(q)} + WI_{(q,t)} - WO_{(q,t)} \quad \forall q \in Q, t \in T: t = 1$ $W_{(q,t)} = W_{(q,t-1)} + WI_{(q,t)} - WO_{(q,t)} \quad \forall q \in Q, t \in T: t > 1$ $\epsilon_{(q)}^{min} \leq W_{(q,t)} \leq \epsilon_{(q)}^{max} \quad \forall q \in Q, t \in T$	$\tilde{\varepsilon}_{(q)}$	0.2	32	(Draman et al., 2021)
	Water outlet, $WO_{(q,t)}$	$WO_{(q,t)} = \varphi_q \sum_{j \epsilon J} FO_{(j,t)} \quad \forall q \in Q, t \in T$ $\theta_{(q,t)}^{min} \leq WO_{(q,t)} \leq \theta_{(q,t)}^{max} \quad \forall q \in Q, t \in T$		1.18	107.28	
Fertilizer mixing	Blending level, $B_{(t)}$	$B_{(t)} = \tilde{\zeta}_{(t)} + BI_{(t)} - BO_{(t)} \quad \forall t \in T = 1$ $B_{(t)} = B_{(t-1)} + BI_{(t)} - BO_{(t)} \quad \forall t \in T > 1$		0.5	80	(Amudha et al., 2021)
	Blending outlet, $BO_{(t)}$ with fertilizer demand, $\xi_{(t)}$	$BO_{(t)} + UW_{(t)} = \xi_{(t)} \quad \forall t \in T$		0.8	40	
	Blending fertilizer outlet, $BOF_{(j,t)}$ with nutrient supply, $NS_{(i,n,t)}$	$BOF_{(j,t)} = \sum_{(i,n) \epsilon JN} \tau_{(n,t)} NS_{(i,n,t)} \quad j \in J, t \in T$				
	Blending water outlet, $BOF_{(j,t)}$ with blending outlet, $BO_{(t)}$	$BOW_{(q,t)} = BO_{(t)} - \sum_{j \epsilon J} BOF_{(j,t)} \quad \forall q \in Q, t \in T$				
Nutrient	Level of nutrient, $NL_{(i,n,t)}$ in plant	$NL_{(i,n,t)} = \tau_{(i,n)} + NS_{(i,n,t)} - NB_{(i,n,t)} \quad \forall i \in I, n \in N, t \in T: t = 1$ $NL_{(i,n,t)} = NL_{(i,n,t-1)} + NS_{(i,n,t)} - NB_{(i,n,t)} \quad \forall i \in I, n \in N, t \in T: t > 1$ $\rho_{(n,t)}^{min} \leq NS_{(i,n,t)} \leq \rho_{(n,t)}^{max} \quad \forall n \in N, t \in T$	$\tau_{(i,n)}$	0.008	113	(Kroggel M. and Kubota C., 2018)
	Nutrient being absorbed by the plant, $NB_{(i,n,t)}$ with nutrient demand, $\sigma_{(i,n,t)}$	$NB_{(i,n,t)} + U_{(i,n,t)} = \sigma_{(i,n,t)} \quad \forall i \in I, n \in N, t \in T: t$		1.3	120	

3. Analysis

3.1 Case study: Optimal Fertigation for Automated Fertilizer Blending System for tomato plant

This study is about the optimal fertigation for an automated fertilizer blending system. Figure 3 depicts the infographic diagram of the case study. The greenhouse size is 4 m x 8 m with 0.5 m spacing between each plant. The drip irrigation network consists of two fertilizer tanks (*j1, j2*), a 5 L water tank (*q1*), and an 18 L blending tank, with a total number of 10 tomato plants (*i1 to i10*). Fertilizer tank *j1* consists of nutrients *n1* and *n5* while fertilizer tank *j2* consists of nutrients *n2*, *n3*, *n4*, *n6*, *n7*, *n8*, *n9,* and *n10*. The substrate soil contained organic matter and had a pH between 5.5 and 6.5, which initially favored plant growth due to its high organic matter content. The drip irrigation has been scheduled for 80 days (*t0 to t80*). The design is similar to the design in Harmanto et al. (2005).

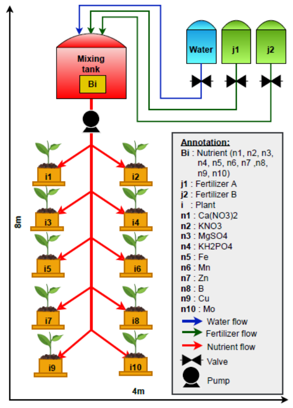

Figure 3: Infographic diagram of the case study

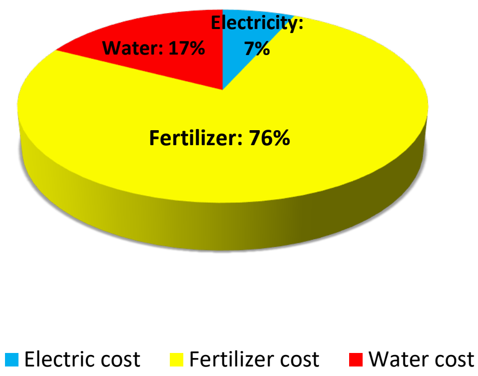

Figure 5: Percentage of the total cost.

3.2 Result: Optimal fertigation of tomato plant

The optimal fertigation schedule has been outlined and the trend of water and fertilizer *j1* and fertilizer *j2* supplied to the tomato plant for 80 days is displayed in Figure 4. The operation of every nutrient for every tomato plant differs according to the needs of the plant for 80 days with four stages of growth plant such as vegetative growth, flowering, fruiting, and ripening.

As can be seen from the picture, fertilizers are mainly used in the 3rd stage (fruiting) and the 4th stage of plant growth (ripening and harvest). The 2nd stage of flowering requires a lot of water because fertilizer could alleviate the negative effect of water stress during the flowering stage (Liu et al., 2019).

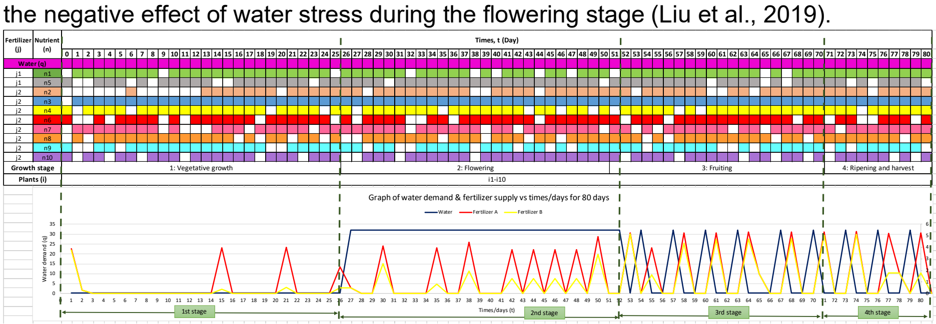

Figure 4: Gantt chart of operation nutrient supply for agriculture in 80 days and Water (L) and fertilizer (mg/L) supply into plants at each period.

Costs are calculated based on mathematical models of data and case studies. Figure 5 shows a percentage of pie chart of the proportion of each expense during the 80 day irrigation and fertilization period, represented by the period from *t0* to *t80*. The results concluded that the highest cost is the fertilizer cost, which accounted for 76 % ($78.10) of the total cost. The reason for this is that nowadays large supply of fertilizers to the plant with essential nutrients like nitrogen needed, so that the crops grow bigger, faster, and produce more food (Cen et al., 2020). The total fertilizer cost for 80 days is $102.91. The cost of daily supplied water is 17 % ($17.92). By using the low horsepower pumps, the total operational costs can be reduced. Although the water consumption is higher than the fertilizer usage, the water cost is the lowest cost due to low water tariffs in Malaysia. The low water tariff is the minimum charge set by National Water Services Commission (SPAN) for Class 1 industrial use less than 200 m^3 at $5.91 per month (SPAN, 2017).

4. Conclusions

The optimal fertigation for AFBS for tomato plants has been successfully developed. The optimisation model of AFBS demonstrates the optimum fertilizer blending system that irrigates the accurate nutrient and water requirements of the plants for every stage of plant growth with 30% minimising of fertilizer use. The result concluded on minimising the total operating cost for fertigation that is mainly based on fertilizer, supplied water, and electricity costs. Conclusively the highest cost is fertilizer cost (76 %), followed by water (17 %) and electricity (7 %) costs. Although the volume of supplied water is approximately ten times greater than the volume of fertilizer, the water price is relatively much lower than the fertilizer price. This trade-off is due to the low water tariff mandated by National Water Services Commission in Malaysia. Therefore, the novelty of this optimisation model of AFBS for fertigation is to represent the ideal condition-based fertigation and to show the effective cost-benefit analysis (CBA). Future research work will focus on cost comparison analysis between time-based fertigation and precise condition-based as the proposed fertigation model for AFBS.

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References

Amudha, T., Thilagavathi, N., & Sangeetha, A. (2021). A systematic study on bio-inspired frameworks for fertilizer optimization. *International Journal of Agricultural Technology*, *17*(4), 1287–1304.

Aziz, D. H. C., Razak, N. H., Zulkafli, N. I., Saat, S., & Tumari, M. Z. M. (2021). Automated Fertilizer Blending System to Reduce Nitrogen Loss and Water Runoffs: A Best Evidence Review. *Chemical Engineering Transactions*, *89*(November), 367–372. https://doi.org/10.3303/CET2189062

Cen, Y., Guo, L., Liu, M., Gu, X., Li, C., & Jiang, G. (2020). Using organic fertilizers to increase crop yield, economic growth, and soil quality in a temperate farmland. *PeerJ*, *8*. https://doi.org/10.7717/PEERJ.9668

Chang, J., Havlík, P., Leclère, D., de Vries, W., Valin, H., Deppermann, A., Hasegawa, T., & Obersteiner, M. (2021). Reconciling regional nitrogen boundaries with global food security. *Nature Food*, *2*(9), 700–711. https://doi.org/10.1038/s43016-021-00366-x

Draman, S. F. S., Shukri, S. M., Ishak, N. S. I., Samad, A. S. A., & Pauzi, A. F. (2021). Optimization of AB Fertilizer for Plant Growth in Fertigation Using Central Composite Design. *IOP Conference Series: Materials Science and Engineering*, *1176*(1), 012010. https://doi.org/10.1088/1757-899x/1176/1/012010

Harmanto, Salokhe, V. M., Babel, M. S., & Tantau, H. J. (2005). Water requirement of drip irrigated tomatoes grown in greenhouse in tropical environment. *Agricultural Water Management*, *71*(3), 225–242. https://doi.org/10.1016/j.agwat.2004.09.003

Kandelous, M. M., Kamai, T., Vrugt, J. A., Šimůnek, J., Hanson, B., & Hopmans, J. W. (2012). Evaluation of subsurface drip irrigation design and management parameters for alfalfa. *Agricultural Water Management*, *109*, 81–93. https://doi.org/10.1016/j.agwat.2012.02.009

Kroggel M. and Kubota C., D. of H. and C. S. (2018). *Hydroponic Nutrient Solution for Optimized Greenhouse Tomato Production*. Agriculture and Natural Resources. https://ohioline.osu.edu/factsheet/hyg-1437

Liu, J., Hu, T., Feng, P., Wang, L., & Yang, S. (2019). Tomato yield and water use efficiency change with various soil moisture and potassium levels during different growth stages. *PLoS ONE*, *14*(3), 1–14. https://doi.org/10.1371/journal.pone.0213643

Mahmud, K., Soetanto, D., & Town, G. E. (2018). Energy Management Softwares and Tools. *Comprehensive Energy Systems*, *5–5*, 202–257. https://doi.org/10.1016/B978-0-12-809597-3.00518-6

Nor, N. A. M., Man, S. H. C., Baharulrazi, N., & Yunus, N. A. (2018). Optimisation of model-based fertiliser formulation for sustainable agriculture. *Chemical Engineering Transactions*, *63*, 49–54. https://doi.org/10.3303/CET1863009

Razak, N. H., Hashim, H., Yunus, N. A., & Klemeš, J. J. (2021). Reducing diesel exhaust emissions by optimisation of alcohol oxygenates blend with diesel/biodiesel. *Journal of Cleaner Production*, *316*(x). https://doi.org/10.1016/j.jclepro.2021.128090

SPAN. (2017). *Water Rates in Malaysia*. Suruhanjaya Perkhidmatan Air Negara. https://www.span.gov.my/document/upload/AtBz79IrBNcxpXRh9R2SXYAcr1cAZ5oK.pdf

Tim Stobierski. (2019). *Cost-Benefit Analysis: What It Is & How to Do It | HBS Online*. Harvard Business School Online. https://online.hbs.edu/blog/post/cost-benefit-analysis

Zulkafli, N. I., & Kopanos, G. M. (2016). Planning of production and utility systems under unit performance degradation and alternative resource-constrained cleaning policies. *Applied Energy*, *183*, 577–602. https://doi.org/10.1016/j.apenergy.2016.08.060

Zulkafli, N. I., & Kopanos, G. M. (2018). A general optimization framework for the design and planning of energy supply chain networks: Techno-economic and environmental analysis. *Chemical Engineering Research and Design*, *131*, 214–233. https://doi.org/10.1016/j.cherd.2017.11.043