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Enhancing Techno Economic Efficiency of FTC Distillation Using Cloud-Based Stochastic Algorithm

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ABSTRACT

A liquefied petroleum gas plant facility (LPGPF) is a series of binary distillation columns used to separate natural gas into four alkanes: ethane, propane, butane, and pentane. The conventional distillation column design consists of three binary distillation columns and six heat exchangers to perform the process. Each heat exchanger consumes immense energy to heat up the reboiler and condense the distillate. There are several process technologies that can minimize distillation column energy consumption. In this research, a fully thermally coupled distillation column (FTCDC) was proposed to minimize energy consumption by reducing the number of heat exchangers and tray columns. An FTCDC has the capability to reduce capital expenditure, operational expenditure, and total annual cost (TAC). The complexity of the FTCDC arises from its process integration. In each column, the intersection composition depends on complex mass and energy balances at the column inlet and outlet and each tray. Process integration, including material recycling and heat recovery, increases the complexity significantly. Moreover, the decision variables are multi-intersection composition for each column to achieve optimum objective function, increasing the number and complexity of the computational load such that effective stochastic optimization algorithms are required. The proposed method was designed using a rigorous vapor liquid equilibrium (VLE) FTCDC model and incorporated with recent stochastic optimization algorithms, such as a genetic algorithm, particle swarm optimization (PSO), an imperialist competitive algorithm, and a duelist algorithm, to determine hydrocarbon composition in the FTCDC intersection. To increase the efficiency and effectiveness of the FTCDC optimization design, cloud computing was utilized. The result was compared with conventional methods such as Fenske-Underwood-Gilliland, a Fenske-Underwood-Gilliland modification, and VLE. The optimization objective function is to minimize TAC with hydrocarbon composition in the FTCDC intersection as decision variables. The optimization using the VLE-PSO method reduces TAC up to 26.28%. All designs were validated using a rigorous model with Aspen HYSYS commercial software. This study's primary goal is to improve the performance of FTCDCs using stochastic algorithms and cloud-based computing capacity. The large amount of computation is handled by cloud-based computing resources, enabling reliability and durability.

KEYWORDS

Cloud-Based Application, Gas Plant Facility, Liquefied Petroleum, Optimization, Stochastic Algorithms

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INTRODUCTION

Distillation columns are the preferred process to separate two or more products/components. Today, over 40,000 columns are operating worldwide. Each consumes 40% or higher of the total energy consumption or operating cost of the plant (Battisti et al., 2020; Kiss & Smith, 2020). In a typical liquefied petroleum gas plant facility (LPGPF), natural gas consisting of four components can be separated using three conventional columns and three different sequences. The first option is a direct process, in which most volatile components would be recovered and become distillate first. The second option is an indirect process, in which the heaviest component would be recovered and become the bottom product first. The third option is a distributed sequence that would be a mid-split comprising two to three distillation columns (Celenza, 2019; Shahruddin et al., 2017). Each conventional column requires a reboiler and a condenser that intensify energy consumption. Alternatively, Petlyuk columns can be utilized to minimize energy consumption.

The process of distillation involves the separation of a liquid and/or vapor mixture of two or more substances into the component fractions of desired purity by both the application and the removal of heat. Distillation separations are performed for about 95% of all fluid separations within the chemical industry, and this requires an enormous amount of energy. There are different kinds of configurations used to carry out the distillation separation, developed so as to minimize the energy consumption involved in the operation. Reduction of energy consumption provides economic benefits along with a reduction in the emissions associated with the use of fossil fuels (Kooijman & Sorensen, 2022). One such configuration is the thermally coupled distillation system. This was first proposed by Wright, and then the theoretical studies were performed by Tumbalam Gooty et al. (2023). The fully thermally coupled distillation sequence is also referred to as the Petlyuk column.

Although the Petlyuk column was introduced much earlier, half a century ago, it was not commercially implemented until now because of its operation and its design. With respect to the separation of tertiary mixtures, a fully thermally coupled distillation column (FTCDC) requires minimal energy when compared to a conventional distillation system that uses two distillation columns in various compositions of the feed (Zhu et al., 2021) . The energy saving that happens in FTCDC stems from eliminating the remixing of the intermediate component in the first column and then the reduction of mixing effect in the feed stage of the conventional distillation column design (Dünnebier & Pantelides, 1999).

The salient feature of an FTCDC lies in the use of a prefractionator through which a non-sharp split of light, medium, and heavy components into two products happens. The top product of the prefractionator contains light and medium components, while the bottom contains medium and heavy components. These products are then introduced into the main column of the unit by the thermal coupling arrangement of the top and the bottom prefractionator. In the end, the components that are present in the main column are completely separated into three distinct products. One of the major sources of separation inefficiency that is seen in a conventional multicomponent distillation is the remixing effect; for the Petlyuk column arrangement, it is the prefractionator that reduces the remixing, thus resulting in energy savings. This significant reduction in the remixing inefficiency is provided by a non-sharp split in the prefractionator. Also, this prefractionator reduces the mixing that occurs at the feed tray in a conventional distillation unit.

Because distillation columns account for the largest contribution of total energy consumption of the chemical process due to their high heat demand, there is a pressing need for an energy-efficient column design to reduce carbon-dioxide emissions. This will also help reach the climate goals of the chemical industry. The new distillation arrangements such as the dividing-wall columns (DWCs), internally heat-integrated columns, and other multi-effect columns show that there could be a potential for a high reduction of energy consumption in the distillation process.

In order to save energy, researchers, academicians, and scientists proposed the use of a thermally coupled distillation column so as to reduce the excess consumption of energy. An FTCDC involves the thermal coupling of vapor-liquid streams between a prefractionator and the main distillation column, ensuring that the arrangement reduces any significant separation losses that may happen in the process and also reducing the remixing effect. It also forges efficient interactions between the two phases of liquid and vapor in the column. Parallelization and cloud computing are some of the known opportunities to enhance the modeling step process significantly.

A Petlyuk column comprising three fully thermally coupled distillation columns becomes a single column, a reboiler and a condenser only. Hence, FTCDCs can save energy consumption or reduce operational expenditure (OPEX) and also reduce capital expenditure (CAPEX). In the oil and gas refining industry, distillation columns are frequently used. Hence, FTCDC utilization could reduce capital investment by about 30% and energy costs by about 40%. A multicomponent mixture is fed to the column. The lightest component moves upward and is the top product, while the heaviest component moves down and is the bottom product. An intermediate component that initially moves both upward and downward subsequently separates out from the top as well as the bottom and is produced as a side stream (Abid et al., 2018).

Utilization of an FTCDC requires coordination between three stand-alone columns in a direct or indirect sequence, especially in mass energy balances. It saves costs by using a single condenser and reboiler. In an FTCDC, purity is high for all streams reached due to reduced remixing effects; it has high thermodynamic efficiency; and it has lower operational costs, also due to integration design. It requires low energy in comparison to the conventional separation process and has a small footprint (SDG programs) (Jiang et al., 2019).

The important use of an FTCDC is to separate the middle section into two columns. The feed is being fed to a prefractionator, and the side stream that is removed and recovered from the other side is primarily the intermediate component (Biyanto et al., 2017). The problems arise from the determination of the proper mixture content of the four components in each intersection. It is rare that research papers describe how to determine and optimize the intersections mixture. Optimization of the FTCDC design consists of a nonlinear and integer model. Hence, it is considered a mixed-integer nonlinear problem (MINLP).

In general, a MINLP is a complex problem that requires a stochastic optimization technique to reach global optimum. Stochastic optimization algorithms are based on adaptive random search methods that require only the objective function and the constraints and not derivatives (Ashok Kumar & Sivakumar, 2022). Many recent stochastic algorithms have been proposed in the literature, such as a duelist algorithm (DA), a genetic algorithm (GA), particle swarm optimization (PSO), and an imperialist competitive algorithm (ICA) (Biyanto et al., 2017; Lin et al., 2023). There are statements that no algorithm is superior to others or the no free lunch theorem (Dhal et al., 2019), and very rare utilization of recent stochastic algorithms is found in the literature on the application of FTCDC design optimization. Hence, the comparison of these algorithms in the FTCDC design optimization case is valuable. In the internet of things (IoT) business era, the optimization of FTCDC design can be performed using cloud computing.

Cloud applications have become an important and well-known emerging computing environment that supports on-demand and provides internet-based services. Cloud applications allow a range of services and tools to be easily accessed from anywhere in the world (Manikandan et al., 2022). Hence, cloud applications have become a globally accessible way to optimize the design of FTCDC (Rahaman et al., 2022).

In previous research, the design of an FTCDC was based on mass and energy balances determined by collecting data from existing plant data process flow diagrams manually. Doing it that way is time consuming, cannot be accessed from everywhere, provides limited data, and has a high potential for error due to lack of updated data, human error, and misinterpretation. To improve the effectiveness and quality of FTCDC design, the utilization of cloud-based computing is required. Nowadays, cloud-based computing provides huge resources, high reliability, and good durability. Cloud apps allow engineers to access, analyze, control, and optimize big data from numerous sources in real time.

In order to develop an intelligent technique to obtain the best design solution, improve design efficiency, and minimize reliance on experience in the design process, research utilizing cloud application-based design has been proposed. A design methodology based on the GA-BP (back propagation) model was proposed by Ye et al. (2023). Data regarding distillation-column optimization (Stergiou et al., 2021), including feed composition, temperature, pressure, and flow rates, may be included in this data (Gaurav et al., 2022). Furthermore, cloud-based applications facilitate the interchange of ideas, processes, and best practices by enabling seamless communication among physically separated teams (Mamta et al., 2021). Users may model and simulate the behavior of FTC distillation columns under various conditions thanks to cloud-based simulations, which help with decision-making (Tripathi & Kumar, 2022).

The way that businesses manage data and computation has been revolutionized by cloud computing. Cloud apps allow professionals in the sciences to access and analyze data from numerous sources in real time regarding distillation column optimization (Stergiou et al., 2021). Variables, including feed composition, temperature, pressure, and flow rates, may be included in this data. Furthermore, cloud-based applications facilitate the interchange of ideas, processes, and best practices by enabling seamless communication among physically separated teams (Petropoulos et al., 2022). Users may model and simulate the behavior of FTC distillation columns under various conditions thanks to cloud-based simulations, which help with decision-making (Tripathi & Kumar, 2022). The incorporating of cloud computing in FTCDC design can be seen in Fig. 1.

The aim of this paper is to optimize FTCDC design-based cloud computing using recent stochastic optimization algorithms, i.e., GA, ICA, PSO, and DA, to achieve minimal total annual cost (TAC) by determining the optimum intersections mixture. The optimization results would be compared with two empirical design methods, Fenske-Underwood-Gilliland and a Fenske-Underwood-Gilliland modification, and a trial-and-error method, a vapor liquid equilibrium model.

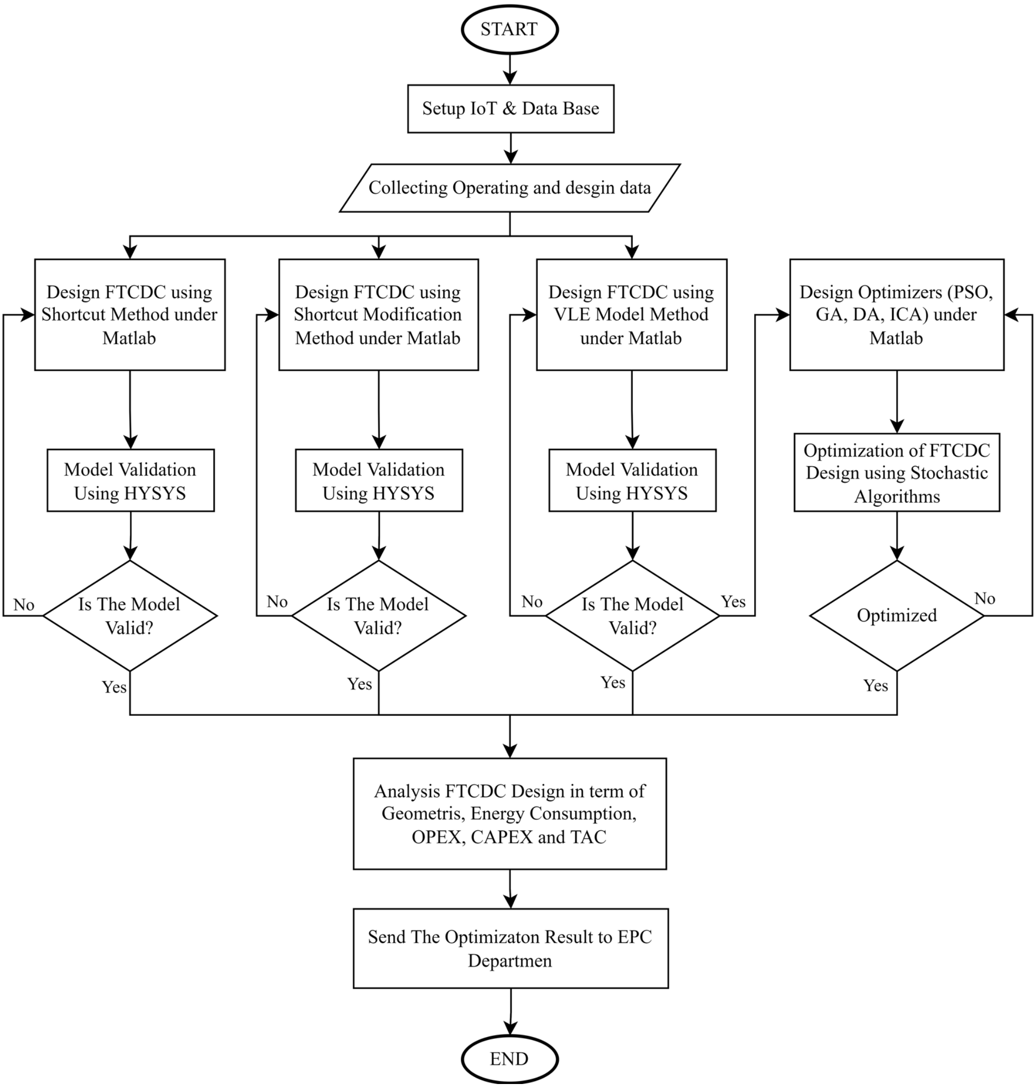
The methodology starts from data collection consisting of operational data and existing design data. The data are read using IoT from historical plant data. Modeling, validation, and optimization were performed using MATLAB. The optimization results were validated using HYSYS software before being sent to the Engineering Procurement Construction department or another company.

RELATED WORK

One of the most important unit operations and processes that take place in the chemical industry is chemical reactions, mass transfer, and fluid-mixture separation. Distillation is understood to be the preferred liquid-separation technique in the petrochemical and oil-refinery industry. However, what is alarming is the energy consumption that is used by this distillation operation (Li et al., 2023), which stands at 3% of the world's total energy consumption. About 70% of the energy expenses that are associated with running process plants are also contributed by the operational cost of the unit. Therefore, to meet environmental requirements and be conscious of the repercussions on the environment, more efficient designs and operation of these distillation columns must be implemented. Taking this step can help ease ever-increasing energy demands and greenhouse-gas emissions. In comparison to the conventional column configurations, a complex configuration of a distillation unit can result in lower capital investment and lower energy consumption (Truckenbrodt et al., 2019).

With globalization, market consumption has increased. A significant amount of the energy consumption in the world comes from distillation operations. This consumption, however, can be significantly reduced by using distillation columns that are complex, such as the divided-wall distillation column (Abid et al., 2018). The process industry is looking to maximize productivity at a minimal operational cost, and with a divided-wall column, there is energy and investment savings. Distillation consumes a lot of energy mainly because of the evaporation and condensation states. In general, more than half of the heat energy that is present in the column reboiler is used to evaporate the liquid to the top and to condense the vapor that comes from it again. For this, FTCDCs will help

Figure 1. FTCDC design-based cloud computing



save energy consumption significantly. The model was developed by Wright in 1947, and further development from the theoretical side came from Petlyuk in 1960. According to Petlyuk's theory, the inefficiency that is present in the distillation process can be mitigated by combining the reboiler and condenser at the prefractionator with the main column (Zhang et al., 2022).

Another way to reduce the operating cost and the installation cost compared to traditional distillation systems is by using DWCs, which are intensified processes that have attracted both industrial and academic fraternity (Segovia-Hernández et al., 2020). The simulation of DWCs using the Petlyuk system has been studied extensively and reported on by many scholars. The problem, however, is that the commercial simulators do not have any blocks for dividing-wall columns as the standard models do (Buitimea-Cerón et al., 2021). This means the design of DWCs requires adapting the available blocks of conventional columns with the help of thermal coupling to integrate the Petlyuk column. Due to the additional degrees of freedom in the DWCs, the DWCs are generally regarded as more complex than the traditional distillation columns. Therefore, to have a preliminary design of the DWC structure before conducting a rigorous simulation, one has to initialize the degrees of freedom, which are the design parameters such as the feed stage, the number of stages in each of the sections, the reflux ratio, and the vapor and liquid split ratios. What becomes challenging is the choice of the values for setting these degrees of freedom, since this decision can affect the column efficiency as well.

Heat exchanger networks (HENs) is one technique that is used within the process industries to recover heat from the hot stream before sending it to the next processing (Pavão et al., 2019). Crude preheat train, or CPT, is one of the typical HENs that is used in petroleum refineries and is also the first step in processing to preheat the crude oil before it is distilled into other petroleum products in a crude distillation unit (CDU). The products obtained from a CDU are also used as heating fluid in the CPT. When certain fluids such as crude and product pass through heat exchangers in CPT, they tend to show fouling tendencies (Biyanto et al., 2016). This fouling causes an efficiency loss with time and also a loss of production due to the downtime that is needed for cleaning and other maintenance. Note that this fouling cannot be avoided but can only be mitigated. The Engineering Sciences Data Unit has reported that fouling in CPT is a serious issue costing about US$4 billion annually for some of the major industrialized nations. Hence, from both an environmental and economic perspective, the motivation is to minimize fouling while at the same time maximizing heat recovery in heat exchanger networks. In most of the processes of distillation, what contributes to the major operating cost is the cost of reboiler duty that is supplied to the distillation column. To counter this, minimizing the reboiler heat input can lead to minimizing the operating cost (Lee et al., 2019). As of now, there are a few distillation technologies that reduce energy consumption for a multicomponent system. Out of these, DWC is the most promising one.

A global optimization framework for determining the minimum cost required in order to distill any multicomponent mixture was introduced into individual constituents using a sequence of columns, known as global minimization algorithm for cost, an extension of the global minimization algorithm introduced by Jiang et al. (2019). A multicomponent distillation is omnipresent in the chemical and process industry and is used in the world's largest separations, such as crude oil fractionation and natural gas liquids separations. Although a range of distillation configurations are used to perform these separation tasks, the operating cost and capital required vary. Thus, it becomes imperative to devise techniques that will help engineers identify configurations in a way such that the total cost for these incur a given separation task is close to maximum. However, to be able to identify alternative configurations, it is necessary to characterize the regular configurations. Since the number of regular-column configurations increases rapidly based on the number of components in the feed, researchers are now keen on formulating an optimization problem that can consider all the configurations and identify lucrative options.

In order to apply the principles and technical knowledge involved in designing and developing software, engineers are equipped with producing scalable complex and sophisticated applications. Cloud computing has been identified as the ideal choice for the development of modern software, since it affords engineers a novel way of developing real-time, cost-effective, and quality software (Lin et al., 2023). Cloud computing is also attractive because it can provide a flexible and resourceful platform for development and deployment. The real-time availability and the accountability feature of cloud setup are another attraction for organizations to shift toward this paradigm. However, the prime purpose of cloud computing is not merely providing the basic functionality, which is development and deployment, but also the overall management of the infrastructure.

CONVENTIONAL AND PROPOSED METHODS

In conventional design, LPGPFs separate ethane, propane, butane, pentane, etc. from natural gas by utilizing three binary distillation columns and six heat exchangers. Nowadays, IoT allows operators to monitor the process from any location with an internet connection through cloud-based remote monitoring and control (Mamta et al., 2021) and store the information in a database. To optimize the manner of separation, cloud-based systems can use cutting-edge data analytics and machine-learning techniques (Joshi et al., 2022). The flexibility of cloud computing to include or eliminate distillation columns makes it simpler to increase or decrease the separation performance as needed (Ahmed et al., 2022). LPGPFs using conventional distillation columns cause huge energy consumption and high operational and capital costs (Al-Sobhi & Elkamel, 2015). Hence, the design and operating condition of existing conventional columns of LPGPFs can be used as raw data for efficient FTCDC. The existing conventional column of LPGPFs is shown in Figure 2.

Multicomponent separation using distillation columns has been studied since 1949. Many methods have been proposed to reduce energy consumption and capital cost. One of the methods used is FTCDC (Fakhroleslam & Sadrameli, 2019; Rahimi et al., 2015). The FTCDC configuration is shown in Figure 3.

The FTCDC configuration was first designed in 1965. It consists of a prefractionator and a main column. In theory, this configuration design can save energy due to the use of a boiler and a condenser (Ghadrdan, 2014). FTCDCs could reduce the capital investment by about 30% and the energy cost by about 40%. The FTCDC configuration in LPGPFs consists of a prefractionator and two main columns. The main reason for preparing this configuration is to avoid thermodynamic losses in the mixing process of different streams in the feed tray (Biyanto et al., 2017). Calculating the parameters of the FTCDC configuration uses methods such as Fenske-Underwood-Gilliland, a Fenske-Underwood-Gilliland modification, and vapor liquid equilibrium (Buitimea-Cerón et al., 2021; Le, 2014).

In this research, there are seven methods with and without optimization, i.e., Fenske-Underwood-Gilliland as a shortcut, a Fenske-Underwood-Gilliland modification as a shortcut modification, VLE, VLE optimization using a genetic algorithm (VLE-GA), VLE optimization using an imperialist competitive algorithm (VLE-ICA), VLE optimization using particle swarm optimization (VLE-PSO), and VLE optimization using a duelist algorithm (VLE-DA).

In the shortcut and the shortcut modification, the number of trays and the energy consumption are determined by empirical formula; the VLE method is determined by mass and energy balances. All of them provide the number of trays for each column by the given intersection composition from designer. It may provide low CAPEX; on other hand, however, it causes high OPEX due to targeted composition and throughput, and finally the TAC becomes very expensive. In order to reduce the TAC, an optimization method is proposed. A stochastic optimization method is proposed due to the

Figure 2. PFD of conventional columns of LPGPFs

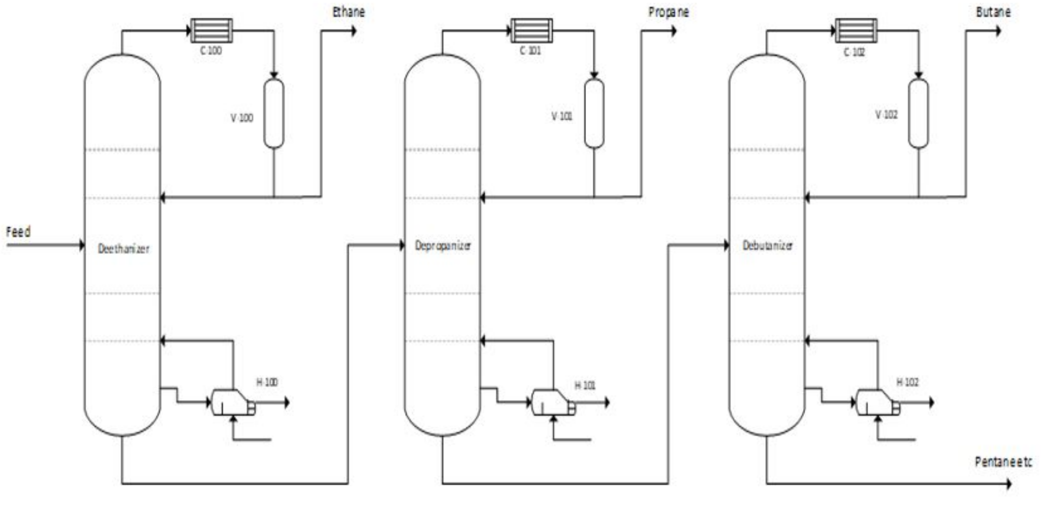
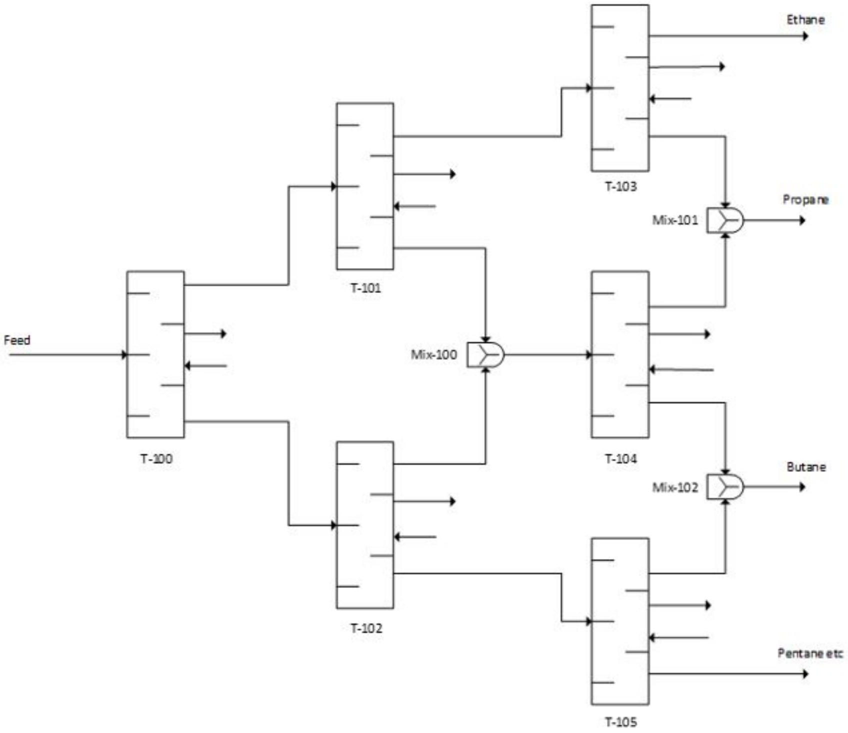


Figure 3. FTCDC configuration



complexity of the model used. The complexity of the FTCDC model arises from the process integration. In each column, the intersection composition depends on complex mass and energy balances at the column inlet and outlet and each tray. Process integration includes material recycling and heat recovery, increasing the complexity significantly. Moreover, the decision variables are multi-intersection composition for each column to achieve optimum objective function; this will increase the number and the complexity of the computational load. The objective function can be formulated as follows:

$$TAC = \frac{CAPEX}{Payback\ Period} + OPEXOjct \tag{1}$$

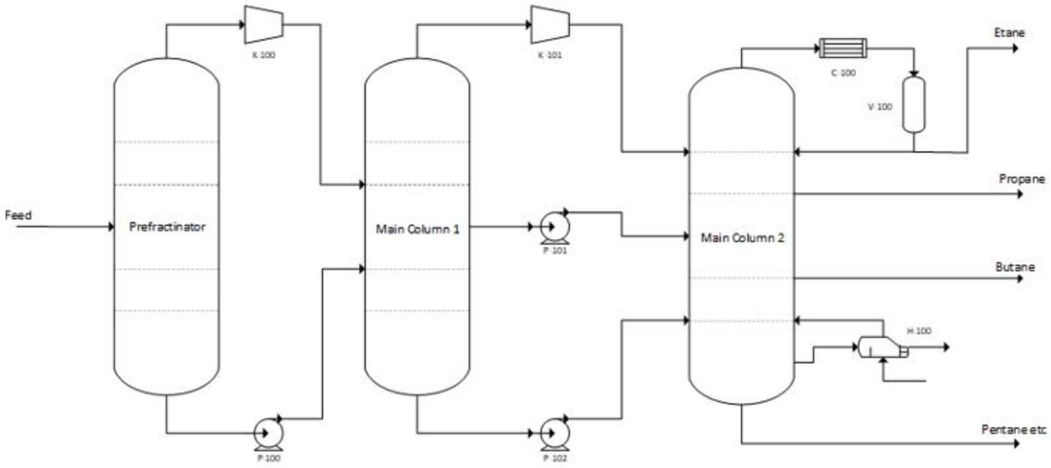
The minimum TAC will be used as the best criterion to evaluate the effectiveness of the proposed stochastic algorithms.

In order to validate the optimization results of all design methods, the rigorous FTCDC models in LPGPFs have been simulated using Aspen HYSYS commercial software. The design results would be analyzed in terms of CAPEX and energy efficiency OPEX as well as TAC. The schematic diagram of the rigorous FTCDC model is shown in Figure 4.

RESULTS AND DISCUSSION

The design of the FTCDC without optimization was performed using shortcut modification and VLE to determine FTCDC design parameters such as the minimum number of trays, the actual number of trays, and the optimal feed stage sequentially for each column as three binary distillation columns. In

Figure 4. The rigorous FTCDC model of LPGPF



the VLE method, the saturation pressure and saturation temperature were calculated using the Peng-Robinson equation. However, by trial and error or heuristic method. In the VLE model using some stochastic optimization algorithms, intersection mixture compositions are determined by stochastic optimization techniques utilizing the optimization parameters in the literature. The distillation column designs with and without optimization results are shown in Table 1.

The number of trays varied for each design method, causing the slight CAPEX difference. In this research, the total CAPEX of the number of LPGFs is calculated from the number of column trays times the tray unit price and installation cost per tray. Since the LPGF is designed for 20 years, the annual CAPEX can be simply calculated from total CAPEX divided by 20 years. The results show that the CAPEX of LPGFs using conventional and FTCDC columns is almost the same. It is well known that the distillation column is an energy-intensive unit operation. Hence, the annual OPEX is very high compared to the CAPEX (Fig. 5).

The OPEX of FTCDCs is lower than that of conventional distillation columns due to removing the reboiler and condenser at the intermediate section of the column. The difference in OPEX between FTCDC designs is because of number of trays and feed tray number for each column section will provide different reboiler energy consumption, as shown in Table 1 and Table 2.

Table 1. FTCDC geometry for each design method

Parameter	Shortcut	Shortcut Modification	VLE	VLE-GA	VLE-ICA	VLE-PSO	VLE-DA
Trays of prefractionator	43	53	48	35	41	28	28
Trays of main column 1	39	44	53	56	52	55	62
Trays of main column 2	149	155	143	134	139	141	127
Feed into the prefractionator	1	3	2	2	2	3	4
Feed into the main column 1	9 and 32	3 and 29	3 and 28	14 and 45	13 and 38	14 and 42	15 and 44
Feed into the main column 2	3, 78, and 140	43, 87, and 149	34, 78, and 122	26, 64, and 119	34, 74, and 120	32, 75, and 118	34, 78, and 121
Side stream main column 1	21	10	12	25	29	21	32
Side stream main column 2	42 and 80	50 and 88	49 and 94	38 and 90	47 and 92	46 and 89	44 and 88

Figure 5. CAPEX comparison for each method

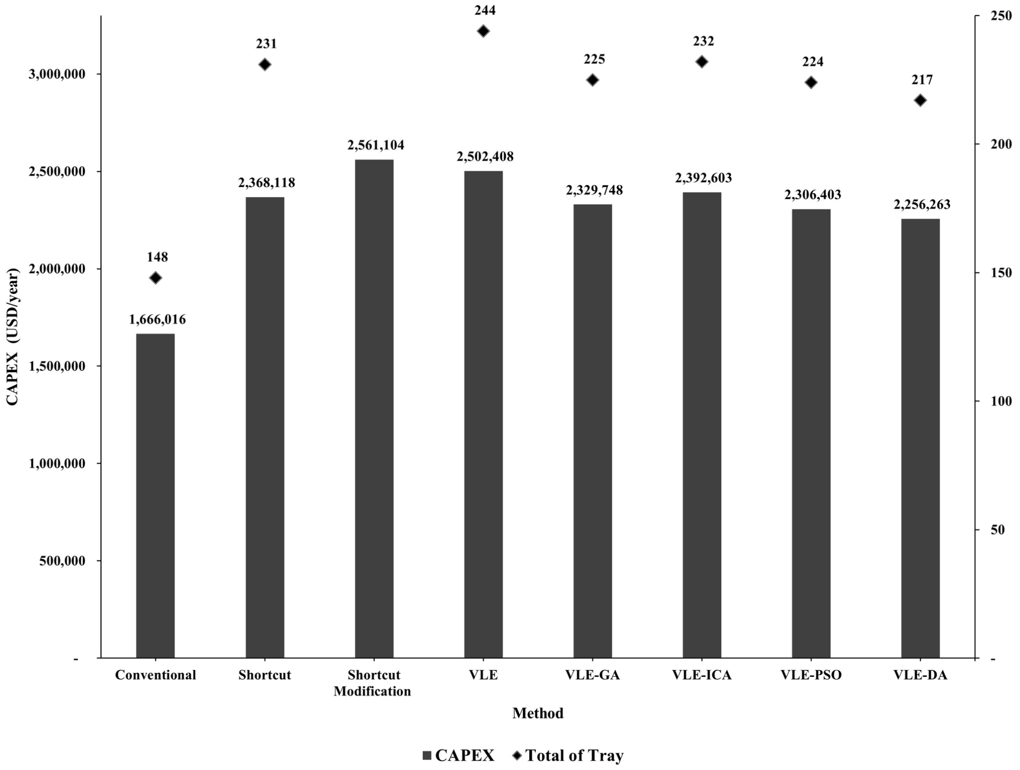


Table 2. FTCDC energy consumption for each design method

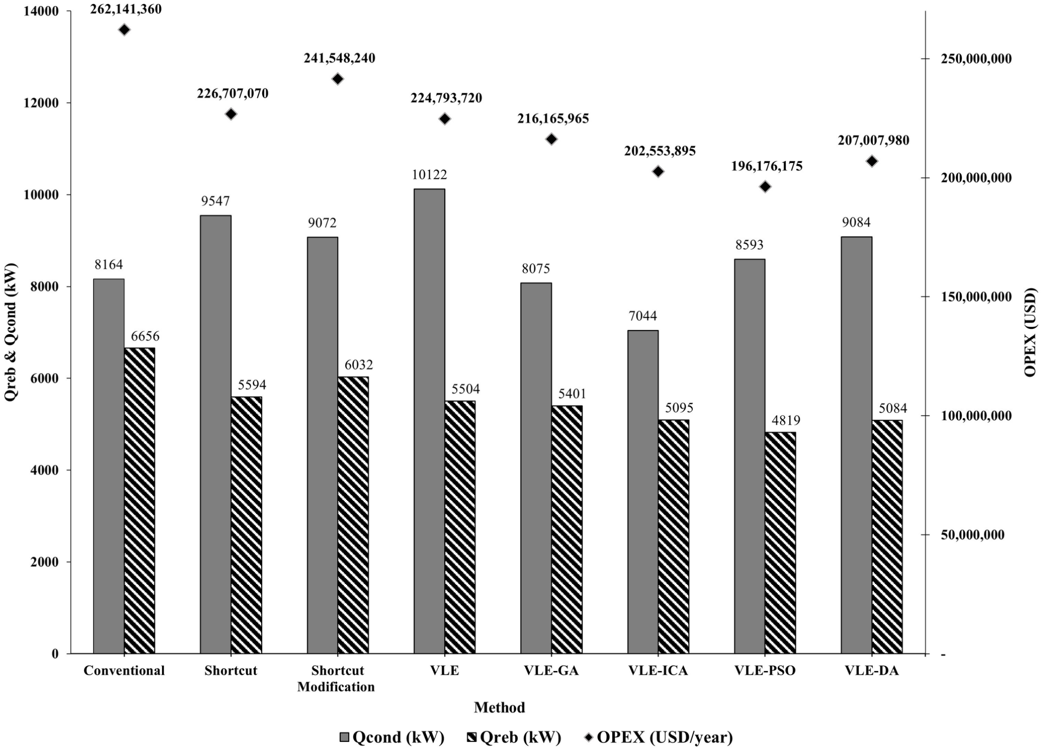
Energy (kW)	Shortcut	Shortcut Modification	VLE	VLE-GA	VLE-ICA	VLE-PSO	VLE-DA
Q condenser	9,547	9,072	10,122	8,075	7,044	8,593	9,084
Q reboiler	5,594	6,032	5,504	5,401	5,095	4,819	5,084

The design using a rigorous model without optimization (VLE) required the highest energy. Its mean trial and error method is not suited to solving complex problems such as FTCDC design. Empirical methods such as shortcut and shortcut modification provide better performance in terms of energy consumption than the VLE method. The complexity of the FTCDC design using a rigorous VLE model will be solved using a stochastic algorithm. It shows that all VLE incorporated with an optimization method provides the lowest energy consumption (in kilowatts), especially VLE-DA (Table 2). Hot and cold energy have different unit prices, which affects OPEX. Hence, the lowest OPEX is provided by VLE-PSO (Figure 6).

The total expenditure or total annual cost for conventional column and FTCDC is tabulated in Table 3 and Fig. 7. The design of FTCDCs using the shortcut method can reduce TAC by 14.75%, modification of the shortcut method by 9.2%, VLE method by 14.86%, optimization of the VLE method with PSO by 26.28%, with DA by 21.91%, with GA by 18.69%, and with ICA by 23.25% per year compared to conventional distillation column design.

The complexity of FTCDC design in LPGPFs provides a different TAC. It depends on the design objective used in each method. Shortcut and modified shortcut methods focus on sizing of

Figure 6. OPEX comparation for each method



the column using an empirical approach. The VLE method focuses on an accurate column model and is suitable for rigorous simulation. Since optimization required three components, i.e., realistic objective function, an accurate model, and suitable optimization technique, the design of FTCDCs using VLE incorporated with a stochastic optimization method provides the best result.

The lowest number of trays will provide the lowest CAPEX. Design of FTDCs without optimization will provide the lowest number of trays and CAPEX. The CAPEX will increase if a

Table 3. Annual cost

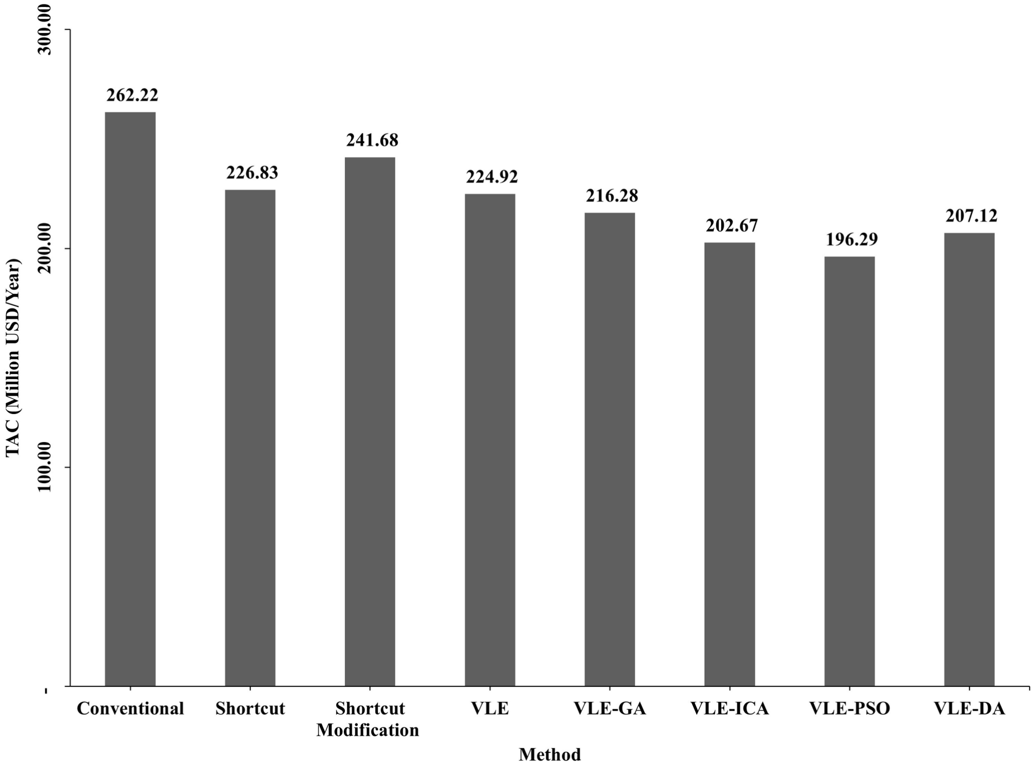
Method	CAPEX (Million $/year)			OPEX (Million $/year)		TAC (Million $/year)
	Pre-Fractionator	Main Column 1	Main Column 2	Reboiler Energy Cost	Condenser Energy Cost	
Conventional	0.56	0.56	0.54	242.71	19.43	262.22
Shortcut	0.49	0.46	1.42	203.99	22.72	226.83
Shortcut Modification	0.59	0.50	1.47	219.96	21.59	241.68
VLE	0.54	0.59	1.37	200.70	24.09	224.92
VLE-GA	0.42	0.62	1.30	196.95	19.22	216.28
VLE-ICA	0.47	0.58	1.34	185.79	16.76	202.67
VLE-PSO	0.34	0.61	1.35	175.72	20.45	196.29
VLE-DA	0.34	0.67	1.24	185.39	21.62	207.12

more rigorous model is utilized due to the increasing amount of uncertainty. This complexity has been solved by the optimization of FTCDC design, since the utilized the TAC as objective function, VLE as rigorous model and stochastic optimization as optimization technique, the optimization of FTDC design provide best results especially VLE-PSO.

In sizing design details, each method provides different decision parameters, i.e., number of trays. Empirical approaches such as shortcut and modified shortcut methods provides that the number of trays in the prefractionator is 43 and 53, the number of trays at main tray column 1 is 39 and 44, and the number of trays at main column 2 is 149 and 155, respectively. The VLE method provides that the number of trays in the prefractionator is 48, the number of trays at main tray column 1 is 53, and the number of trays at main column 2 is 143 trays. Meanwhile, the parameter of number of trays using the stochastic algorithm, i.e., GA, ICA, PSO, and DA, provides that the number of trays in the prefractionator is 35, 28, 17, and 41; the number of trays at main tray column 1 is 56, 62, 49, and 52; and the number of trays at main column 2 is 134, 127, 141, and 139, respectively.

In terms of operational point of view, the simulation result shows the smallest condenser energy consumption was obtained from the design using the VLE-ICA method, while the smallest reboiler energy consumption was obtained from the design using the VLE-PSO method. Finally, from an economic point of view, the design of FTCDCs using stochastic algorithm methods (GA, ICA, PSO, DA) provides lower TAC than without optimization. In between them, the lowest TAC was provided by PSO of $196.29 million per year.

Figure 7. Total annual cost



CONCLUSION

The proposed design optimization of FTCDCs in LPGPFs by utilizing the VLE model incorporated with and without optimization using recent stochastic optimization algorithms has been carried out. The optimization results show that FTCDC design optimization is proven to reduce energy consumption due to the reduction of heat exchangers as reboiler and condenser, and the optimization objective function is TAC, utilizing an accurate model (VLE) and suitable optimization technique (stochastic algorithms). The most significant reduction in total annual cost was obtained with the VLE-PSO method and was 26.28% compared with the conventional method. The effectiveness, revenue generation, and long-term viability of several manufacturing operations could be transformed by incorporating cloud-based stochastic algorithms into four-component FTC distillation columns. Industries may stay competitive by adopting data-driven, adaptive optimization tactics and help create a more ecologically friendly and sustainable future. The conclusions drawn from this study present a strong argument in favor of further investigation and application of these methods in real-world industrial settings.

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DATA AVAILABILITY STATEMENT

The original contributions presented in the study are included in the article/supplementary material; further inquiries can be directed to the correspondence author.

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The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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