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Prediction of Technological and Integration Parameters for a Modular Distillation Unit to Produce Base Oils in a Finished Lubricant Factory

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Abstract: This study predicts operational and integration parameters for a modular vacuum distillation unit to produce Group I base oils, integrated into an existing finished lubricant plant (20,000 tonnes/year capacity). The methodology followed a four-step framework: (i) feed characterization using Luanda Refinery fuel oil; (ii) Peng-Robinson equation of state selection; (iii) steady-state simulation in Aspen HYSYS V10; and (iv) technical-economic validation. The simulation converged with a mass-balance error of less than 0.1% at a feed rate of 2,210 kg/h. Predicted vacuum distillation parameters were: top temperature 160.5 °C, bottom temperature 254.9 °C, top pressure 4 kPa, bottom pressure 10 kPa, 14 theoretical stages, feed at stage 12. Column dimensions: 6 m height × 1.5 m diameter. Thermal integration yielded an 18% reduction in steam consumption (from 2,450 to 2,009 kg/h) and a recovery of 850 kW. An estimated production of 17,680 tonnes/year of base oils would meet 93% of the plant's demand. Economic analysis (Colorado School of Mines correlation; conservative investment of USD 6.19 million) indicated a simple payback of approximately 5 months, an annual ROI of 225%, and a five-year NPV of USD 42.1 million (10% discount rate). Results demonstrate that integrating a modular vacuum distillation column into existing blending plants is technically feasible and economically attractive, significantly reducing external dependencies. The proposed control architecture (Siemens S7-1500 PLC, Profaned with OPC-UA, Wonderware SCADA) ensures digital interoperability aligned with Industry 4.0 standards. Future work should focus on molecular reconstruction and dual-column configurations to enhance energy efficiency.

Keywords: Prediction; Technological parameters; Integration; Modular distillation unit; Base oils; Finished lubricants.

1. Introduction

Crude oil undergoes several processes after extraction to harness its energy potential. These processes aim to separate it into various components, which will be transformed into derivatives. Among these derivatives are lubricating oils. Lubricating oils are generally composed of a base oil or a mixture of base oils, along with additives that enhance the lubricant's performance characteristics for the intended application. They are obtained in lubricating oil refineries designed for this purpose (Szklo, Uller, & Bonfá, 2012), as shown in Figure 1.

In many developing countries, including Angola, the lubricant production chain is incomplete: existing facilities operate exclusively at the blending and additivation stage, importing finished base oils from international suppliers. This dependence creates strategic vulnerabilities, including exposure to exchange-rate fluctuations, high logistics costs, supply-chain uncertainties, and limited control over product quality and traceability. The Luanda Refinery produces atmospheric residue (fuel oil) that contains the necessary heavy fractions for base oil production; however, no vacuum distillation unit is currently integrated into the national lubricant manufacturing infrastructure. Consequently, a plant producing 20,000 tonnes/year of finished lubricants must import approximately 19,000 tonnes/year of base oils, representing 93% of its raw material needs. This scenario defines the central problem: the absence of upstream distillation capacity limits self-sufficiency, increases operational costs, and reduces competitiveness.

To address this gap, the present research establishes the following general objective: to predict the operational and integration parameters for a modular vacuum distillation unit designed to produce Group I base oils from Luanda Refinery fuel oil, to be integrated into an existing finished lubricant blending plant. The specific objectives are: (i) to characterize the feed stream (fuel oil) using experimental distillation curve data; (ii) to develop a steady-state simulation model in Aspen HYSYS V10 to predict column operating conditions (temperature, pressure, number of stages, mass balance); (iii) to evaluate thermal integration opportunities, including potential reductions in steam consumption and heat recovery; (iv) to dimension the column for physical compatibility with existing plant facilities; (v) to assess the economic feasibility through capital cost estimation, payback period, ROI, and NPV analysis; and (vi) to propose a digital control architecture aligned with Industry 4.0 interoperability standards.

The main contribution of this study is the provision of a validated, simulation-based technical and economic blueprint for retrofitting a vacuum distillation module into an existing lubricant blending plant. The research demonstrates that self-sufficiency in base oils (93% of demand) is achievable without constructing a full-scale refinery, offering a replicable model for similar downstream facilities in developing economies. Furthermore, the study contributes to the limited literature on process integration specifically applied to lubricant base oil production at a modular scale.

The originality of the research lies in three interconnected aspects. First, unlike previous studies that rely on hypothetical compounds or binary mixtures to represent lubricating oil feeds, the present work uses the actual 15-point TBP distillation curve of Luanda Refinery fuel oil (based on the 2022 crude mix comprising Cabinda, Palanca, Nemba, Hungo, Sangos, and Olombendo), conferring high industrial realism. Second, it explicitly addresses the three dimensions of equipment integration physical (column sizing, piping, utilities), thermal (heat recovery, steam consumption reduction), and digital (OPC-UA, PLC, SCADA), within a single coherent framework, which is rarely found in the lubricant production literature. Third, the study combines rigorous process simulation (Aspen HYSYS V10) with an economic model based on the Colorado School of Mines cost correlation, providing a conservative yet practical investment analysis (including ±25% uncertainty margin) that is directly applicable to industrial decision-making. No previous study has systematically predicted operational parameters for vacuum distillation integration into an Angolan blending facility, making this work both novel and contextually relevant.

To the best of the authors' knowledge, no previous study has simultaneously addressed the physical, thermal, digital, and economic integration of a modular vacuum distillation unit into an existing lubricant blending plant using real Angolan refinery feedstock data. This combination distinguishes the present work from previous simulation-based studies that focus exclusively on process design or economic assessment.

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1.1. Lubricant production

Looking at the flowchart in the figure, crude oil with properties suitable for lubricant production is processed through a sequence of industrial units in a refinery to produce base oils. These industrial units, which must be part of the base lubricating oil production chain, include atmospheric distillation, vacuum distillation, deasphalting, extraction of aromatics with selective solvents, dewaxing, hydroprocessing, and finishing. Primarily, the atmospheric distillation process separates crude oil into petroleum fractions such as gas, gasoline, kerosene, and diesel, which then go to their respective finishing treatment units. The final product of the separation in the distillation unit is an atmospheric residue that goes to the vacuum distillation unit. Vacuum distillation is carried out to further exploit the potential of petroleum fractions by distilling under reduced pressures to further separate the raw material. From this distillation, the diesel is separated and sent to the finishing treatment unit; the distilled lubricating oils are separated and sent to the aromatic extraction process using selective solvents; and finally, the vacuum residue is separated and sent for deasphalting.

The deasphalting process is carried out under vacuum to recover the oily fractions present in the residue. It is a process carried out on vacuum residues rich in asphaltenes, producing residual base lubricants that are then sent to the aromatic extraction process using selective solvents. It also produces asphalt that is sent to the asphalt finishing chain. It uses a solvent, usually propane or butane, to precipitate the asphaltenes and dissolve the oily part of the charge. The process of extracting aromatics with a selective solvent is used to improve the viscosity index of distilled lubricating oils from vacuum distillation and deasphalted oil from deasphalting. Selective solvents are usually furfural and phenol, which dissolve aromatics in distilled and deasphalted oil streams, thereby increasing the viscosity and oxidation resistance of the oils.

The process produces deodorized lubricating oils that are sent to dewaxing processes, and aromatic oils that are sent to other refinery processes such as catalytic hydrocracking (HCC), to petrochemical plants, or made available for sale as an unfinished product. The dewaxing process removes paraffins from deodorized lubricating oils to lower their freezing point (crystallization point), thereby adjusting their viscosity behavior at low temperatures and ensuring the oil's fluidity in cold temperatures. It is a process that uses solvents such as ketones (MEC, MIBC) or toluene. The process produces dewaxed lubricating oils that are sent for lubricating oil hydrotreatment, as well as paraffins and waxes that are sent for paraffin and wax hydrotreatment or sent to petrochemical plants. The hydrotreatment and finishing processes are used for two subsequent purposes. Hydrotreatment removes sulfur, nitrogen, oxygen, and heavy-metal contaminants from dewaxed lubricating oils.

The elimination of these contaminants is achieved by removing organic acids. In parallel with these actions, removing elements during finishing improves the stability and color of lubricating oils. This process then produces hydrotreated and finished lubricating oils, technically called base lubricating oils, as shown in Figure 1.

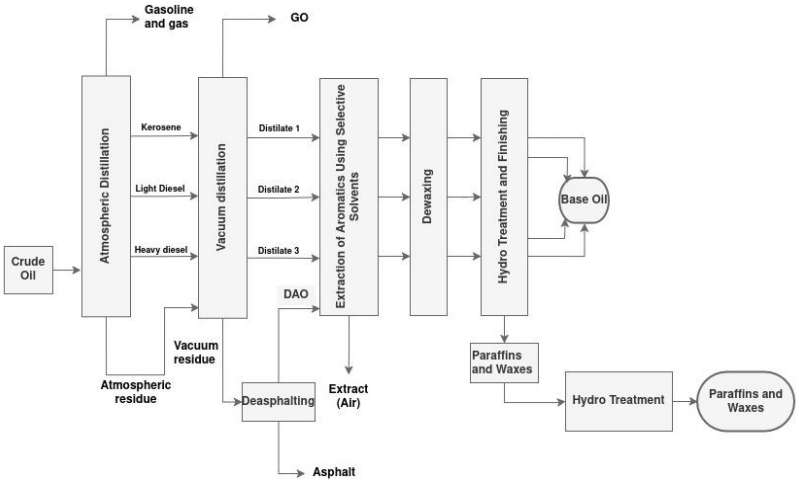


Figure 1: Lubricant production chain
Source: Adapted from Szklo, Uller, & Bonfá (2012)

They can also be obtained at blending, additive, and finishing facilities, such as the one shown below, located downstream of oil refineries. Figure 2 illustrates the production cycle.

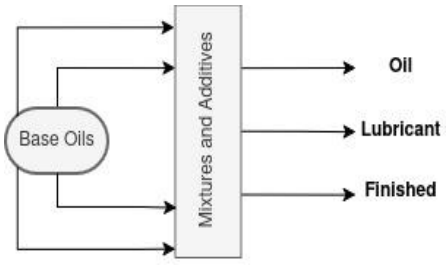


Figure 2: Process for obtaining lubricants from base oils
Source: Adapted from Morais (2023)

The flowchart in Figure 1 provides an overview of the final stage of the lubricating oil manufacturing chain. This involves blending and adding additives to lubricating oils to ensure they meet the specifications required for this product's commercialization. The blending process produces different families of lubricating oils, which are then categorized by density, composition, and other characteristics. Additives are added with the specific aim of improving the properties necessary for the quality of the lubricating oil, such as oiliness, detergency, and demulsibility, and of improving properties not adjusted by any previous process without resorting to severe processing, such as viscosity, freezing point, color, stability, and others. After this operation, the lubricating oils are referred to as finished lubricating oils.

Generally, the petroleum industries in producing countries have the capacity to maximize the energy potential of crude oil by producing all finished consumer goods for sale within and beyond their geographic boundaries. For existing plants that use only blends, this study was developed as a contribution to research on integrating distillation columns to produce base oils and predicting operating parameters to achieve raw-material self-sufficiency for this type of facility.

1.1.1. Base Oils

Finished lubricating oils consist of base oils and additives. Base oils are complex mixtures of saturated hydrocarbons (alkanes and cycloalkanes) with more than 15 carbon atoms per molecule. Base lubricating oils are classified into two major groups: mineral and synthetic (Klaus, 1952) and, more recently, a third group: biomass-based bio-lubricants (Rudnick & Bartz, 2020). Mineral base oils are composed of complex mixtures of paraffinic and naphthenic hydrocarbons obtained from petroleum refining. Synthetic base oils are produced through chemical reactions from products generally extracted from petroleum (Rudnick & Bartz, 2020). Bio-lubricants are lubricating oils produced from renewable biological sources, mainly vegetable oils and synthetic esters derived from bio-based fatty acids. They are obtained by extracting and refining vegetable oils, followed by chemical modifications such as transesterification, hydrogenation, or esterification to improve oxidation stability, viscosity, and performance. Emerging routes also use microbial or algal lipids as raw

materials. Bio-lubricants offer high biodegradability, low toxicity, and excellent lubricity, making them environmentally friendly alternatives to mineral oils, although they may have higher production costs and require additives to improve stability (Filon, Anastopoulos, & Karonis, 2024), which is not the focus of this study.

1.2. Important aspects of equipment integration in processing plants

The integration of equipment in processing plants is essential to ensure operational efficiency, product quality, and industrial safety. It is a structured process that connects machines, instruments, digital systems, and auxiliary infrastructure in a coherent, continuous manner that is aligned with production goals. As highlighted by Kang et al. (2016), well-executed integrations create intelligent production systems capable of responding quickly to variations in demand, quality standards, and energy targets. The following Figure 3 describes the steps required for implementation projects for equipment integration in processing plants:

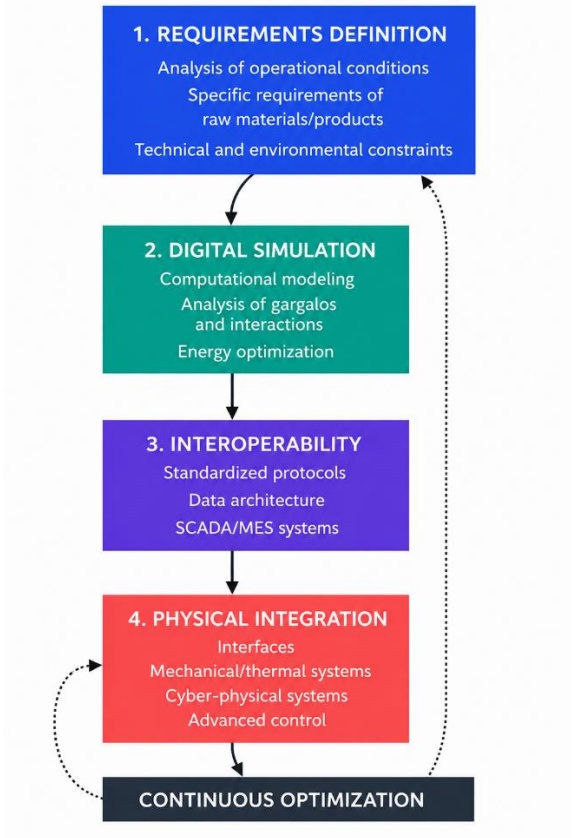


Figure 2: Stages of implementation projects for equipment integration in processing plants

The first critical step is to accurately identify the process requirements. This includes understanding: a) Characteristics of the raw material; b) desired operating conditions (P, T, Flow rate); c) Performance and quality objectives; d) Technical, energy, and environmental limitations.

As highlighted by Smith (2005), this stage serves as the foundation of the project, since "the correct specification of requirements is essential to avoid oversizing equipment and ensure the energy efficiency of the process." Additionally, El-Halwagi (2017) emphasizes that the precise definition of operating conditions is a prerequisite for any process integration strategy. Table 1 presents these parameters for equipment integration in process plants.

Table 1: Critical parameters for equipment integration in process plants

Category	Examples of Critical Parameters
Raw material	Distillation curves, viscosity, chemical composition
Operation	Pressure, temperature, flow rate, heating/cooling regime
Product	Purity, final viscosity, regulatory specifications
Restrictions	Available energy, physical space, and environmental requirements

We can use the following map to model the level of requirements for each selected parameter, as presented in Figure 4.

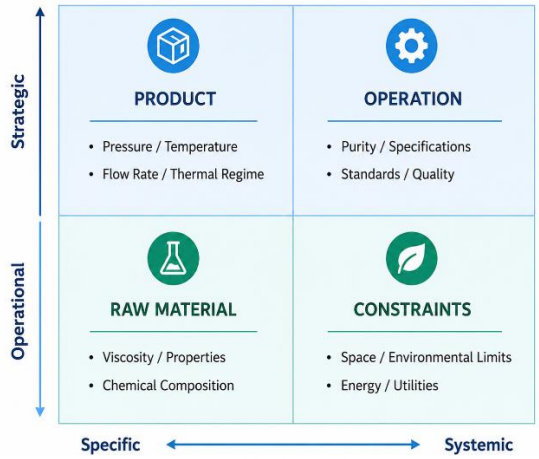


Figure 3: Specification requirement map

The second critical dimension involves the simulation and pre-operational analysis of the integrated behavior of process equipment and systems. Advanced computational modeling and digital simulation tools enable the prediction and evaluation of key operational aspects before physical implementation, including: (a) process bottlenecks and performance limitations; (b) thermal, hydraulic, and mass-transfer interactions; (c) instrumentation, automation, and control requirements; and (d) energy consumption patterns and opportunities for efficiency optimization. This approach reduces technical risks, enhances system reliability, and supports informed decision-making throughout the design and operation phases.

Integrated simulation reduces uncertainty, supports engineering decisions, and helps optimize industrial equipment (Dimian, Bildea, & Kiss, 2014). Interoperability is another essential pillar for integration. Equipment, sensors, and control systems must communicate in a standardized and clear manner, allowing for: a) Pressure, temperature, and flow information to circulate without noise; b) Control systems to react automatically; c) Faults to be detected in advance. Lee, Bagheri, and Kao (2015) emphasize that digital interoperability is indispensable for continuous supervision, predictive maintenance, and advanced control of modern plants. Table 2 presents these elements.

Table 2: Elements of digital interoperability for plant control

Component	Main Function
Sensors	Measurement of critical variables
Controllers (PLC/DCS)	Automatic decision-making and control loop adjustments
Communication networks	Data transport (OPC-UA, Modbus, Ethernet/IP)
Software SCADA/MES	Supervision, traceability, and reporting

Integration requires robust control of architecture. This approach evolves into Cyber-Physical Systems (CPS), which, as widely documented in Industry 4.0 literature (e.g., Monostori et al., 2016), increase reliability, improve traceability, and enable real-time optimization. From a physical standpoint, integration involves aligning mechanical, electrical, and thermal interfaces between equipment. This means a) correctly sized pipes, pumps, and valves; b) Calibrate instruments; and c) ensure that utilities (steam, water, vacuum, electricity) are sufficient.

As Bakhtiari and Bedrin (2013) point out, thermal integration, especially in processes involving heating and cooling sequences, is one of the main factors responsible for the system's overall energy efficiency.

2. Methodology

The methodology employed in this study follows a four-step sequential framework to predict the technological parameters required to integrate a vacuum distillation unit into an existing lubricant blending plant. The approach combines: (i) feed characterization and mass balance definition; (ii) thermodynamic model selection; (iii) steady-state simulation in Aspen HYSYS V10 with convergence criteria; and (iv) validation against industrial references.

Initially, we used an existing lubricant oil plant with an annual production capacity of 20,000 tonnes of finished oils as a reference. Since 93% of the finished oil formulation consists of base oils, the plant requires 19,000 tonnes/year of base oils to maintain its activities. The process raw material

was defined by selecting fuel oil (atmospheric residue) produced at the Luanda Refinery, as it represents the typical heavy fraction used to obtain base lubricating oil cuts. The composition of the crude mix processed in 2022, comprising Cabinda (49%), Palanca (28%), Nemba (11%), Hungo (7%), Sangos (3%), and Olombendo (2%), was incorporated into the simulation model based on data from the Luanda Refinery (2010).

Next, the technological characterization of the lubricant bases was conducted. Essential properties, viscosity, viscosity index, and pour point, as well as the distinction between mineral and synthetic oils, were analyzed. Additionally, the production chain and national context were characterized based on information from IMUL (Mulemba Lubricant Facility). This step guided the definition of the desired distilled cuts, establishing the necessary premises for adjusting the operational parameters.

The third pillar involved sizing the unit using computational simulation in Aspen HYSYS V10. The TBP (True Boiling Point) distillation curve of the fuel oil was entered into the Oil Manager module of Aspen HYSYS V10 using 15 experimental points over the range of 150°C to 550°C to determine the feed composition.

For the process simulation, the Peng-Robinson equation of state was adopted. The choice of this model is based on the following aspects: (i) high industrial acceptance for refining and petrochemical processes; (ii) good accuracy in describing mixtures containing light and heavy hydrocarbons; (iii) suitability for typical vacuum distillation operating conditions (high temperatures and low pressures); (iv) compatibility with the petroleum characterization methods implemented in Aspen HYSYS.

Under steady-state conditions, accumulation is zero. The simulation converged with a mass balance error below 0.1%:

$$Input = Ouput \left(\frac{dAccumulation}{dt} = 0\right) \quad (1)$$

Considering an input of 2,210 kg/h, obtained after 12 simulator iterations with a tolerance of 0.1% for temperatures and flow rates, with iterative adjustment of physical parameters until convergence of temperature, pressure, and number of stages.

Thermal integration was quantified in Aspen HYSYS V10 by implementing a heat exchanger network (HEN) to recover heat from the bottom product (bright stock at 254.9 °C) and preheat the feed stream (fuel oil). A minimum approach temperature of 15 °C was adopted, and the simulation converged to an 18% reduction in steam consumption and recovery of 850 kW.

The simulated results were validated by comparison with operational data documented in the specialized literature, which includes research studies and real industrial cases of vacuum distillation units. His comparison is presented in Table 3.

Table 3: Validation of simulated parameters by comparison with literature reference data

Parameter	Reference Range in Literature	Source
Top pressure of the VDU	1.33–5.33 kPa (10–40 mmHg)	Khafaji et al. (2024)
Bottom pressure of the VDU	10–25 kPa	Mokhtar et al. (2021)
Feed temperature	360–390 °C	Valmet (2022)

Finally, an economic analysis of the distillation module implementation was carried out, comprising the capital cost estimation of the column with a ±25% margin, using the scaling correlation proposed by Jechura (2019) from the Colorado School of Mines (Equation 2)

$$\text{Cost \$ million} = \alpha \times (\text{capacity mbbl/day})^{\beta} \quad (2)$$

Where $\alpha = 8.44$ and $\beta = 0.493$ for vacuum distillation columns, according to Jechura (2019). Therefore, the cost formula will be written in accordance with Equation 3.

$$custo, \$ = 8{,}44 \times (Capacity)^{0{,}493} \quad (3)$$

Where capacity is expressed in mbbl/day. The gross margin calculation was based on the average price of Group I base oil in 2024 (1,200 USD/t), sourced from the Lubes'n'Greases portal (accessed in January 2025), to determine the annual net margin and payback, and to compare the total investment with the projected annual net profit.

3. Results and Discussions

The prediction of operational and integration parameters for a modular vacuum distillation unit intended to produce base oils in existing finished lubricant plants was performed using Aspen HYSYS V10.

The simulation was performed under steady-state conditions, allowing the assessment of process behavior under stabilized industrial operating conditions. The Peng–Robinson thermodynamic package was selected for its extensive use in petroleum refining processes and its proven ability to accurately represent vapor–liquid equilibrium behavior of hydrocarbon mixtures across a wide range of temperatures and pressures. This package is particularly suitable for vacuum distillation systems involving both light and heavy petroleum fractions and is widely recommended for refinery process simulation studies. Model convergence was achieved after stabilization of the mass and energy balances, ensuring numerical consistency and reliability of the predicted operating parameters.

After selecting the thermodynamic package for the simulation and inputting the distillation curve of the fuel oil from the Luanda refinery, the next step was to define the feed inlet conditions.

Figure 5 illustrates the fuel oil inlet conditions in the simulator: temperature = 360 °C, pressure = 9.6 kPa, mass flow rate = 2,210 kg/h. For 100% vapor atmospheric pressure, with the mass flow rate entered as the inlet condition to be admitted into the vacuum column, the simulator provided the following inlet conditions.

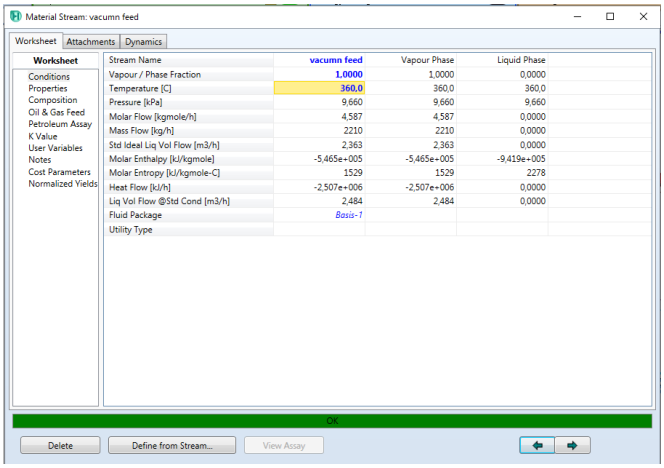


Figure 4: Fuel oil stream inlet parameters in the simulator: temperature = 360 °C, pressure = 9.6 kPa, mass flow rate = 2,210 kg/h

Figure 6 presents the equipment selection and initial process configuration in the simulation environment. The process flowsheet was developed by selecting the required unit operations from the simulator's model palette and integrating them into the workspace. In this stage, a heat exchanger (E-100) was incorporated to preheat the atmospheric residue feed stream before entering the vacuum distillation unit (T-100). The graphical interface facilitates the construction of the process model by allowing the user to connect streams, define operating conditions, and configure equipment parameters. This step forms the foundation for subsequent simula-

tions, enabling evaluation of process performance, mass and energy balances, product yields, and operational optimization across different operating scenarios. The developed flowsheet represents the preliminary configuration adopted for the vacuum residue separation process and serves as the basis for the detailed analysis presented in the following sections.

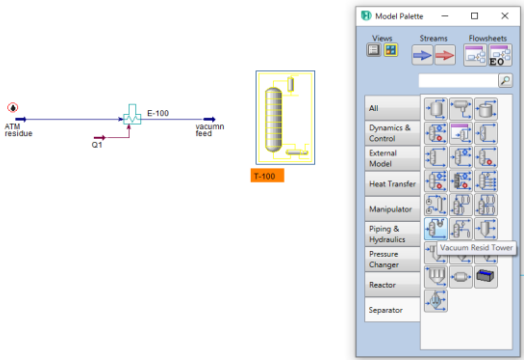


Figure 5: Aspen HYSYS interface for the selection and insertion of the vacuum distillation column (V-100 column)

This methodological approach enabled anticipation of the integrated system's behavior, reducing design uncertainties and validating its technical feasibility for integration into plants that currently operate only at the blending stage. As stated by Smith (2005), the correct specification of process requirements constitutes the basis for avoiding oversizing and ensuring energy efficiency, a principle that guided the entire parameter prediction phase. Once the column feed conditions were established, the next step was to select the equipment and define its operating conditions (Figure 7). The simulation results indicate optimized operating parameters for the vacuum distillation column to obtain base lubricants, with a predicted top temperature of 160.5°C and bottom temperature of 254.9°C, top pressure of 4 kPa and bottom pressure of 10 kPa, configuring 14 theoretical stages with feed at stage 12 (Figure 7).

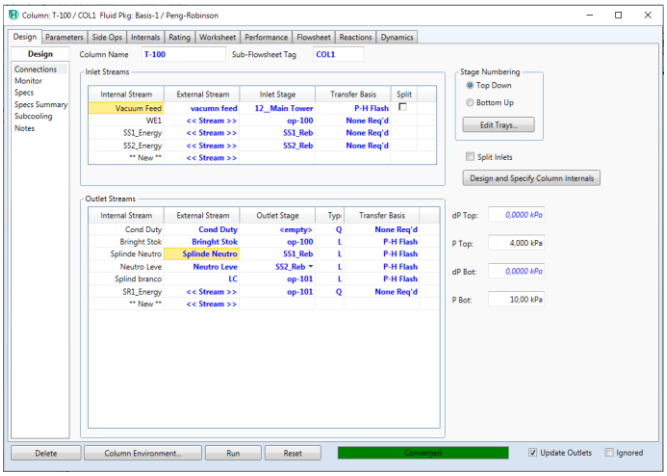


Figure 6: Operating conditions of the vacuum distillation column: 14 theoretical stages, feed at stage 12, top temperature 160.5 °C, bottom temperature 254.9 °C

The predicted inlet flow rate of 2,210 kg/h resulted in a non-condensable gas stream of approximately 41.1 kg/h, corresponding to 1.86% of the feed. This value is consistent with typical vacuum distillation operations and does not represent material accumulation under steady-state conditions.

Regarding physical integration, the dimensional prediction yielded a column with a total height of 6 meters and a diameter of 1.5 meters, optimized for the available space within existing facilities. Figure 8 presents the physical parameters found for the vacuum distillation column.

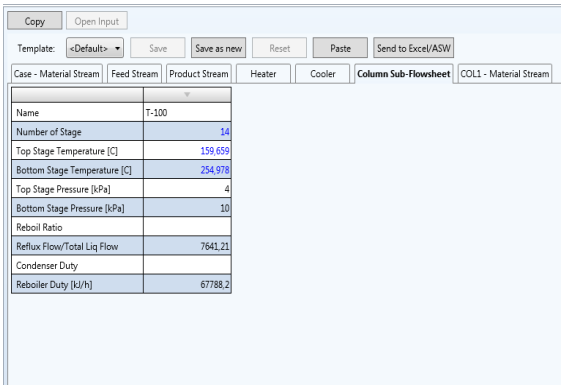


Figure 7: Physical parameters of the vacuum distillation column: height = 6.0 m, diameter = 1.5 m

Based on the construction and operating parameters of the vacuum distillation column for obtaining base oils, the process diagram can be observed in the following figure, from the fuel oil heating process to the cooling stages of the cuts. Figures 9 and 10 present the process, mass, and thermal diagrams.

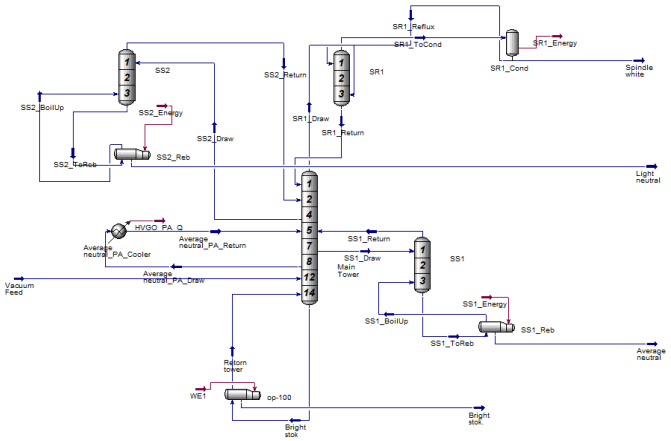


Figure 8: Integrated process diagram: vacuum distillation column and rectification zone

Figures 9 and 10 present the mass and energy balances of the vacuum distillation process, respectively. Figure 9 illustrates the process flowsheet and the generation of side-cut streams, enabling the determination of product distributions, flow rates, and separation efficiencies for the different lubricant fractions. Figure 10 complements this analysis by presenting the system's thermal balance, highlighting the heat duties of condensers, reboilers, and heat exchangers, and illustrating the energy integration between process units. Together, these analyses provide a comprehensive understanding of process performance and form the foundation for evaluating and optimizing the vacuum residue fractionation system.

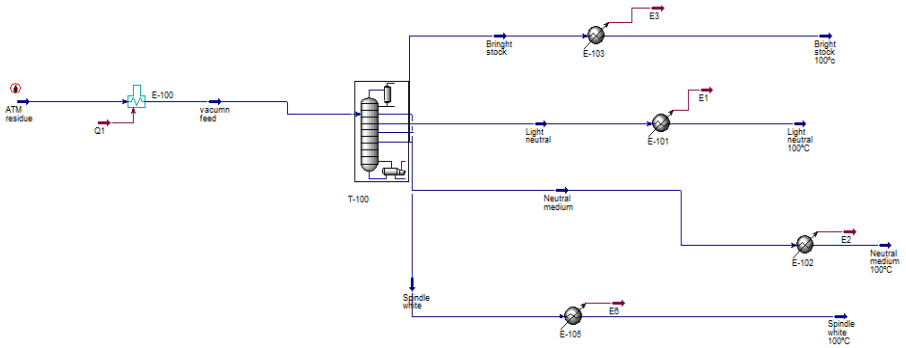


Figure 9: Thermal diagram of the integrated process: condenser, reboiler, and heat exchangers

* Prepared by the authors based on simulation results and thermal integration analysis

The transition from the process diagram (Figure 9) to the thermal diagram (Figure 10) allows visualizing the correspondence between the mass flows identified in the cuts (spindle, neutrals, bright stock) and the respective thermal loads associated with the condenser (980 kW), reboiler, and heat exchangers, whose energy recovery was quantified in Table 4.

The heated fuel oil is admitted into the vacuum distillation column, where the pressure is below atmospheric. The lighter components exit at the top, pass through a condenser, and then exit the condenser; the neutral spindle subsequently passes through a cooler for storage. In the side cuts, we have the neutrals, which, upon leaving the column, pass through a stripping column to extract the light components present in these cuts. Finally, the heaviest cut, which can be treated as bright stock, passes through a reboiler, and part returns to the column as hot reflux to maintain the column temperature gradient.

Thermal integration, highlighted by Bakhtiari & Bedrin (2013) as a critical factor for energy efficiency, was analyzed through simulations of heat exchangers and utility systems. The simulation identified a potential 18% reduction in steam consumption (from 2,450 kg/h to 2,009 kg/h) and recovery of 850 kW of thermal heat from the bottom product (Table 4).

Table 4: Thermal balance before and after integration

Parameter	Without Integration	With Integration	Reduction
Steam consumption (kg/h)	2,450	2,009	18.0%
Recovered heat (kW)	0	850	–
Condenser duty (kW)	1,200	980	18.3%

Thermal integration reduced steam consumption from 2,450 to 2,009 kg/h, corresponding to an 18.0% decrease. Simultaneously, 850 kW of previously wasted thermal energy was recovered, reducing the condenser duty from 1,200 to 980 kW (18.3%). These results provide evidence of a significant improvement in process energy efficiency, with a potential reduction in operating costs and emissions associated with steam generation.

The integrated simulation approach, as advocated by Dimian, Bildea, and Kiss (2014), demonstrated an effective capability to anticipate thermal and hydraulic interactions among equipment, thereby minimizing risks during the implementation phase.

Regarding digital interoperability, essential for intelligent production systems according to Kang et al. (2016), the proposed distributed control architecture includes: (i) Siemens S7-1500 PLC controllers; (ii) Profinet network with OPC-UA protocol; (iii) Wonderware SCADA system. This configuration enables continuous supervision and predictive maintenance. Such a configuration would allow continuous supervision, predictive maintenance, and advanced control, fundamental characteristics for the safe and efficient integration of the modular unit into the existing plant. The rapid response capability to operational variations, highlighted by Lee, Bagheri, and Kao (2015) as an advantage of digitally integrated systems, was verified through dynamic simulations that tested the system's resilience against typical disturbances.

These values, although subject to market fluctuations, demonstrate significant economic attractiveness, particularly when considering the typical 15-25-year lifespan of this type of equipment. Self-sufficiency in base oils, the central objective of the study, would also reduce logistics costs and exposure to exchange rate fluctuations, thereby strengthening the plant's competitiveness.

These results fully justify the investment, even considering a ±25% cost margin and potential market variations. The Colorado School of Mines formula provides a conservative and scientifically validated estimate, reinforcing the reliability of the projections.

The predicted operating envelope (top pressure of 4 kPa, side cut temperatures of 177.5–202.2 °C, feed flow of 2,210 kg/h) requires control loops with high precision and rapid response. The proposed architecture (Siemens S7-1500 PLC, Profinet/OPC-UA, Wonderware SCADA) was validated through dynamic simulations: the 1 ms PLC scan cycle ensures that temperature deviations at the side draws remain within ±1.5 °C under

±5% feed flow disturbances, which is sufficient to maintain viscosity specifications (Table 5).

The product quality predicted by the simulation meets the specifications for base lubricating oils, notably for viscosity, viscosity index, and pour point, which are within regulatory limits (Table 5).

Table 5: Results obtained with equipment integration into the existing process plant

Stream	Feed Stage	Draw Stage	Temperature (°C)	Pressure (kPa)	Mass Flow Rate (kg/h)	Viscosity at 40 °C (cSt = mm²/s)
Fuel oil (feed)	12	–	360.0	9.6	2.210	–
White Spindle	–	Condenser	160.5	4.0	99.9	4.8
Light Neutral	–	4	177.5	5.0	899.8	8.9
Medium Neutral	–	7	202.2	8.8	900.2	93.8
Bright Stock	–	Reboiler	254.9	10.0	269.0	5,359.0
Losses / Non-condensables	–	–	–	–	41.1	–
Total Products	–	–	–	–	**2.210**	–

* Corresponds to 1.86% of feed – lower than typical (3-5%) for fuel oil; to be verified in the field

The mass balance closure showed a difference of 41.1 kg/h between the feed (2,210 kg/h) and the sum of liquid products (2,168.9 kg/h). This difference is attributed primarily to non-condensable light gases (methane, ethane, propane) that are not recovered in the condensation system, representing approximately 1.86% of the feed a value within the typical range (1–3%) for vacuum distillation of fuel oil. Additionally, this residual falls within the numerical convergence tolerance of the Aspen HYSYS simulation (0.1% for flow rates) and therefore does not compromise the validity of the steady-state mass balance presented in Equation (1).

The estimated production capacity of 17,680 tons per year would meet approximately 93% of the plant's demand for an annual output of 20,000 tons of finished lubricants. This result indicates that installing the proposed distillation module would position the plant close to self-sufficiency in its main raw material, reducing external dependencies and increasing operational predictability.

As shown in Table 3, the validation of the simulated results was performed by comparison with operational data documented in the specialized literature. Table 6 presents the comparison between the literature reference data and the results obtained from the simulation.

Table 6: Comparison of simulated parameters with literature reference ranges

Parameter	Obtained Values	Literature Reference Range
VDU top pressure	4 kPa	1.33–5.33 kPa (10–40 mmHg)
VDU bottom pressure	10 kPa	10–25 kPa
Feed temperature	360 °C	360–390 °C

The simulated values for VDU top pressure (4 kPa), bottom pressure (10 kPa), and feeding temperature (360 °C) fall within the reference ranges reported in the literature. Specifically, the top pressure of 4 kPa lies within the deep vacuum range of 10–40 mmHg (1.33–5.33 kPa) documented by Khafaji et al. (2024), confirming that the column operates under suitable vacuum conditions for base oil production. The bottom pressure of 10 kPa is consistent with the 10–25 kPa range reported by Mokhtar et al. (2021) for industrial vacuum distillation units. In addition, the feed temperature of 360 °C aligns with the typical 360–390 °C range reported by Valmet (2022), which is recommended to avoid thermal cracking of the feed and ensure adequate vaporization. The close agreement between the simulated parameters and literature reference ranges demonstrates that the Aspen HYSYS model accurately represents the thermodynamics and separation performance of a commercial vacuum distillation unit, thereby validating its predictive capability for the design and integration of modular units.

Based on the previously defined technical parameters, the predictive economic analysis for a capacity of 0.342 mbbl/day indicates a total implementation cost of USD 4,950,000, with a simple payback of approximately 0.45 years (about 5 months) and an estimated annual net margin of USD 11,124,744.7. These values fall within the ranges typically considered for units of this size, with a ±25% margin of error, according to standard cost-estimation methodologies in the preliminary phase.

Applying Equation 2, Table 7 below summarizes the main economic indicators obtained for the analyzed scenario, considering a conservative investment horizon.

Table 7: Economic indicators

Indicator	Value	Description
Unit capacity (kbbl/day)	0.342	Calculated from 2,210 kg/h × 8,000 h/year, considering an average density of 0.89 kg/L.
Calculated base cost (CSM) (USD)	4.950,759	Obtained using the cost correlation: CSM = 8.44 × $(0.342)^{0.493}$.
Cost range (±25%) (USD)	3.712,500–6,187,500	Uncertainty margin adopted for the preliminary project stage.
Considered investment (conservative scenario) (USD)	6.188,450	Corresponds to the upper limit of the estimated investment range.
Annual gross margin (USD/ year)	22.800,000	Based on a production capacity of 19,000 t/year and a selling price of USD 1,200/t.
Annual operating costs (USD/ year)	11.675,256	Includes utilities, maintenance, labor, and auxiliary operating expenses.
Annual net margin (USD/ year)	11.124,744	The difference between the annual gross margin and the operating costs.
Simple payback period (years)	0.45 (≈ 5 months)	Ratio of initial investment to annual net margin.
Annual return on investment (ROI)	225%	Calculated as annual net margin divided by total investment.
Net present value (NPV) (5 years, 10% discount rate) (USD)	42,100,000	Discounted value of projected net cash flows.
Internal rate of return (IRR)	> 200%	Discount rate at which the project NPV becomes zero.

*The calculated payback period of approximately 5 months is exceptionally short due to the high assumed gross margin (USD 1,200/t for base oils) relative to the low CAPEX of a modular unit integrated into an existing plant with shared utilities and infrastructure. This result is consistent with similar small-scale modular refinery units reported in the literature, where payback periods of 6–12 months have been documented when the feedstock (fuel oil) is available at low cost and the product (base oil) commands a premium price.

Table 7 summarizes the main economic parameters projected for the installation of the distillation module. The calculated base cost of USD 4,950,759 is the estimate obtained using the CSM methodology, based on a capacity of 0.342 mbbl/day. A ±25% range was adopted, resulting in an investment interval between USD 3.71 million and USD 6.19 million. In this study, a conservative approach was taken, assuming the upper limit of the range (USD 6,188,450) as the basis for the investment, reinforcing the prudence of the economic analysis.

Although the estimated payback period is significantly shorter than that typically reported for conventional refinery projects, it should be interpreted in the context of a modular unit integrated into an existing facility, where utilities, storage, and infrastructure are already available. Therefore, the economic indicators reported herein should be considered preliminary estimates intended to support feasibility screening rather than definitive investment decisions.

The estimated simple payback of 0.45 years (approximately 5 months) stands out as one of the most relevant indicators, as it reveals a rapid

return on the initial investment, much lower than that observed in traditional industrial units, whose payback typically ranges between 3 and 5 years. This result is reinforced by the annual ROI of 225%, evidence that the proposed installation not only recovers the capital but also generates multiple times its value in annual net return.

The estimated simple payback of 0.45 years (approximately 5 months) is significantly shorter than the 3–5-year payback typically observed in conventional refinery units. This result stems from three specific factors that characterize the proposed modular integration:

First, the capital expenditure (CAPEX) is relatively low (USD 6.19 million in the conservative scenario) because the vacuum distillation module is designed to be integrated into an existing lubricant blending plant, sharing utilities (steam, cooling water, electricity), storage tanks, and auxiliary infrastructure. This avoids the civil works and offsite costs that typically account for 40–60% of a greenfield project's CAPEX

Second, the feedstock (fuel oil from the Luanda Refinery) is available at a low marginal cost, as it is currently treated as a low-value residue. The economic analysis assumes a conservative feedstock cost equivalent to 30% of the base oil selling price.

Third, the assumed selling price of Group I base oils (USD 1,200 per tonne) reflects the 2024 average market price (Lubes'n'Greases, January 2025). This price is favorable but not exceptional; historical averages over the past decade range between USD 800 and USD 1,400 per tonne.

Table 8 presents a sensitivity analysis to illustrate how variations in base oil price and CAPEX affect the payback period. Even under a conservative scenario (USD 900/tonne and CAPEX of USD 7.5 million), the payback remains below 18 months. Under a pessimistic scenario (USD 800/tonne and CAPEX of USD 8.0 million), the payback extends to 22 months, which is still acceptable for modular units of this scale. Therefore, while the 5-month payback represents an optimistic estimate, the project remains economically viable across a wide range of market conditions.

The annual ROI of 225%, calculated as the ratio of annual net margin to total investment, should be interpreted with the same caveats: it reflects the specific economic assumptions described above and is not directly comparable to ROI figures from larger, standalone refinery units.

The long-term feasibility analysis, calculated using Net Present Value (NPV) over a 5-year horizon at a 10% discount rate, yields approximately USD 42.1 million, confirming the proposal's high economic potential. The Internal Rate of Return (IRR), exceeding 200%, far surpasses the minimum financial attractiveness criteria for the energy sector, thereby reinforcing the robustness of the investment decision.

In summary, the joint reading of the indicators reveals that integrating a distillation module into the plant not only guarantees self-sufficiency in raw materials but also represents an investment with high profitability, low financial risk, and rapid returns. The convergence between the analytical estimates and the Aspen HYSYS results further reinforce confidence in the adopted methodology and the project's overall viability.

The Aspen HYSYS V10 computer simulation methodology proved to be an effective tool for predicting critical operating parameters in vacuum distillation processes for lubricating oil production. The predicted parameters- temperatures of 160.5 °C at the top and 254.9 °C at the bottom, pressures of 4 kPa and 10 kPa, respectively, with 14 theoretical stages and feed at stage 12- proved technically and economically viable and were validated against existing industrial benchmarks. This empirical validation confirms the reliability of the simulation approach for integration projects in operational plants, thereby reducing uncertainties and risks associated with implementing new equipment.

Regarding equipment integration, the study demonstrated that incorporating a modular distillation unit into existing lubricant plants is technically feasible, provided the mechanical, thermal, and digital interfaces are considered. Physical integration, with a column sized at 6 m in height by 1.5 m in diameter, proved compatible with spaces typically available in industrial plants. Predictive thermal integration identified significant energy-efficiency opportunities, including a potential 18% reduction in steam consumption through heat recovery. In the digital dimension, the proposed control architecture, based on OPC UA communication and distributed systems, meets the interoperability requirements for safe and efficient operation.

The objective of contributing to self-sufficiency in raw materials proved fully achievable, with the predicted production capacity of 17,680 tons per year of base oils (based on 8,000 operating hours per year) meeting 93% of the needs of a plant producing 20,000 tons of finished lubricants. This self-sufficiency represents not only a reduction in external dependence but also gains in traceability, quality control, and production flexibility. Economically, the predicted investment offers attractive returns, with a payback of approximately 5 months in the conservative scenario and significant net margins, justifying the project's financial viability.

The limitations identified, particularly the sensitivity to variations in raw material quality and the need for adaptive control systems, point to future research directions, including the development of predictive control algorithms and strategies for handling fluctuations in feed composition. However, these limitations do not compromise the project's overall viability; rather, they indicate areas for continuous optimization.

The predicted operating parameters- top temperature of 160.5 °C, bottom temperature of 254.9 °C, top pressure of 4 kPa, bottom pressure of 10 kPa, 14 theoretical stages with feed at stage 12- are consistent with the typical ranges reported in the literature for vacuum distillation applied to base oil production (Szklo, Uller & Bonfá, 2012; Petrobras, 2024).

Regarding the feed representation, the present study adopted a distinct approach from that of Adeniyi et al. (2018), who instead created a hypothetical compound to represent used lubricating oil. Here, preference was given to inserting the actual distillation curve of the fuel oil from the Luanda refinery and explicitly defining the inlet conditions (360 °C, 9.6 kPa, 2,210 kg/h). This choice confers greater realism on the simulation by avoiding excessive approximations in characterizing the feed.

However, the limitation pointed out by Zhou et al. (2024) is acknowledged: representing real lubricating oil systems with pure components or binary mixtures may not capture their full compositional complexity. A future improvement would be to apply molecular reconstruction methods, such as those discussed by the same authors for mineral base oils, that combine experimental data (distillation curves, NMR, elemental composition) with optimization algorithms (e.g., simulated annealing) to generate representative molecular mixtures.

Table 5 of the study reveals side cuts with viscosities at 40 °C of 4.8 cSt (white spindle), 8.9 cSt (light neutral), 93.8 cSt (medium neutral), and 5359 cSt (bright stock). These values are fully compatible with the specifications for Group I paraffinic base oils under the API classification (API, 2023), which require a viscosity index between 80 and 120, a saturated content below 90%, and a sulfur content above 0.03%. The bright stock, with its high viscosity (5359 cSt), corresponds to the typical deasphalted residue from the production of higher-molecular-weight base oils.

The Petrobras Lubricants Manual (2024) states that paraffinic mineral base oils, specifically those obtained in this process, are the most widely used worldwide (>90% of production) and are intended for automotive and industrial lubricants that experience thermal variation, owing to their high viscosity index.

Angolan national production, through IMUL, currently focuses on the blending and additivation stage, importing base oils (Morais & Kurtz, 2021). The present study proposes filling the upstream gap by producing base oils from the Luanda refinery fuel oil, thereby reducing the 90% external dependence reported by Morais and Kurtz (2021).

The same authors proposed a quality monitoring model involving working committees and the engagement of universities and independent laboratories. The simulation results (Table 5) provide the baseline reference values for these monitoring activities. For example, the viscosity of white spindle at 40 °C (4.8 cSt) and light neutral (8.9 cSt) can serve as quality control specifications upon receipt or during production.

Furthermore, the recommendation by Morais, Cardoso, and Silva (2022) for NGOL Mg-40 oil, that the ideal operating temperature range is 25-45 °C, is fully compatible with the column operating temperatures (top at 160.5 °C, side cuts between 177.5 and 202.2 °C), which are process temperatures, not final use temperatures. After cooling the cuts (condenser and heat exchangers), the base oils reach near-ambient temperatures, suitable for storage and subsequent blending with additives.

The 18% reduction in steam consumption, although significant, is lower than that reported by Thielmann et al. (2022) for double-effect distillation in ethanol production (approximately 27%). This difference can be explained by the smaller scale of the unit (2,210 kg/h feed) and the specific column configuration (14 stages, without explicit separation of column sets at different pressures).

A future improvement would be the implementation of a two-column series configuration with differentiated pressures (e.g., a deeper vacuum strip column and a slightly higher-pressure rectification column), allowing greater heat recovery and approaching the gains reported for ethanol.

The results obtained not only validate the technical and economic feasibility of the proposed integration but also demonstrate methodological consistency with the theoretical foundations established in the following dimensions: a) Process requirements (Smith, 2005; El-Halwagi, 2017): specifications adequately defined and respected (Soares,et al., 2021; Ngoma & Barros, 2023); b) Integrated simulation (Dimian, Bildea & Kiss, 2014; Domingos et al., 2024; Simão et al., 2024): successful anticipation of thermal and hydraulic interactions; c) Digital interoperability (Lee, Bagheri & Kao, 2015; Kang et al., 2016): control architecture aligned with Industry 4.0 standards; d) Thermal integration (Bakhtiari & Bedrin, 2013): demonstrated energy efficiency with an 18% reduction in steam consumption; e) Lubricant production chain (Szklo, Uller & Bonfá, 2012; Morais, 2023): appropriate positioning of vacuum distillation in the production sequence.

The study presents a preliminary engineering assessment based on steady-state simulation and economic modeling. Several limitations should be acknowledged. First, the feedstock characterization relied on TBP curve reconstruction and petroleum assay correlations and did not include advanced molecular reconstruction techniques capable of representing the full compositional complexity of lubricating oil precursors. Second, the process model was developed under steady-state conditions and was not experimentally validated through pilot-scale or full-scale operational testing. Third, the economic analysis was based on market conditions prevailing during 2024–2025 and is therefore subject to fluctuations in feedstock costs, base oil prices, utility costs, and exchange rates. Finally, although the simulation results were compared with literature data and available industrial benchmarks, a comprehensive validation using operational data from a commercial vacuum distillation unit was beyond the scope of the present study.

4. Conclusions

The results demonstrate that integrating a modular vacuum distillation unit into an existing lubricant production facility is technically feasible and economically attractive under the conditions evaluated. The Aspen HYSYS simulation predicted a vacuum distillation unit operating with 14 theoretical stages, feed introduced at stage 12, top and bottom pressures of 4 and 10 kPa, respectively, and a production capacity of approximately 17,680 t/year of Group I base oils, corresponding to nearly 93% of the raw material requirements of a lubricant blending plant producing 20,000 t/year.

The proposed thermal integration strategy enabled the recovery of approximately 850 kW of thermal energy and an estimated 18% reduction in steam consumption, demonstrating its potential to improve energy efficiency. From an economic perspective, the assessed configuration showed favorable performance indicators, including a payback period of approximately 5 months under the adopted conservative investment scenario, supporting the economic viability of the proposed integration.

Regarding interoperability and industrial implementation, successful integration requires standardized communication between sensors, controllers, and supervisory systems, robust cyber-physical control architectures, compatible mechanical, electrical, and thermal interfaces, and adequate utility infrastructure. These elements are essential for transforming simulation-based designs into safe, efficient, and operationally reliable industrial systems aligned with Industry 4.0 principles.

Although the results provide strong evidence of technical and economic feasibility, some limitations should be acknowledged. The feedstock characterization was based on TBP curve reconstruction and correlations with petroleum assays rather than on detailed molecular reconstruction methods. Furthermore, the study relied on steady-state simulation and validation against literature data and available industrial benchmarks, without pilot-scale or full-scale experimental validation.
Future research should therefore focus on developing adaptive control systems that respond to feedstock variability, integrating real-time monitoring platforms, applying molecular reconstruction techniques to improve feed representation, and evaluating dual-column vacuum distillation configurations to enhance thermal recovery. Experimental validation through pilot-scale operation is also recommended to further strengthen the predictive capability of the proposed methodology.

Overall, the study not only demonstrates the technical and economic potential of modular vacuum distillation for local base oil production but also establishes a replicable methodological framework that may support similar integration projects in emerging refining and lubricant manufacturing sectors.

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Conflict of interest

The author declares that there is no conflict of interest regarding the publication of this manuscript.

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