11-2022

Comparison of Two Capital Cost Assessment Methods for A Styrene Process Design

Marian K. Luzier

Comparison of Two Capital Cost Assessment Methods for A Styrene Process Design

by

Marian K. Luzier

Undergraduate honors thesis under the direction of

Dr. Adam Melvin

Department of Chemical Engineering

Submitted to the LSU Roger Hadfield Ogden Honors College in partial fulfillment of the Upper Division Honors Program.

November, 2022

Louisiana State University
& Agricultural and Mechanical College
Baton Rouge, Louisiana

Table of Contents

Chapter 1: The Objective for Chemical Engineering Students in a Process Design Course is to Craft a Manufacturing Process.

Chemical engineering process design involves selecting and integrating a series of processing steps in order to design a manufacturing process than produces a product at desired specifications. [1] Process design endeavors give chemical engineers the opportunity to utilize their creative skillset; these projects are often the most rewarding and satisfying tasks they will undertake in their career. [2] At Louisiana State University (LSU), the process design course, CHE 4172 or "Plant Design"—as it is more commonly known to students, is a one-semester senior-level course. The course is conducted five days per week with two parts—lectures and recitations. Throughout the course of the semester, the students complete the design of an entire manufacturing process. Each semester, a different manufacturing process is designed. Prior to the conclusion of the semester, the process design is presented to industry judges. Students work in teams of four to complete the process design project. Throughout the design process, students gain critical experience with various aspects of the design process, such as equipment sizing, economic analysis, utility optimization, and capital cost assessment. Alongside technical skills, careful participation in such a project gives students the opportunity to heighten interpersonal skills such as communication, presentation skills, technical writing skills, and problem solving. CHE 4172 is unique in comparison to courses in other disciplines in that there is no solution in mind when the problem is presented. While students are given the necessary tools to achieve the objective, they are empowered to brainstorm and problem solve to present a viable solution. Each semester, an industrial partner is selected to familiarize students with the manufacturing process chosen for design. The industrial partner operates a similar process in their own facility. This partner offers a presentation detailing the process as it operates in their own facility and, if possible, a facility tour to the students. These interactions with the industrial partner occur early in the semester so students have a better understanding of the process design they will complete. This industrial partner also participates in the project judging at the end of the semester.

Throughout the semester, various engineering topics are covered in the lecture section of the course. Some of these topics include process design strategy, separations, environmental considerations, ethics, piping, heat exchanger design, and pressure relief device (PRD) design. Students are tested frequently on course material and design progress through weekly quizzes and recitations; this ensures that students are on track with the course material and design. Basics of the design and key parameters are given in the Project 1 Assignment Document—provided by LSU Professional in Residence Barry Guillory. [3] No two teams' design will look exactly alike as teams may choose differing equipment operating specifications, cross exchange networks, and design alternatives to minimize capital and operating costs. Designs are completed using Aspen Plus V12 Process Simulation software—or "Aspen" as it is commonly known. Aspen is a computer software that quantitatively models a manufacturing process; it has various functions such as process simulation, optimization, design specification, sensitivity analysis, and economic analysis, amongst others. [4] Aspen is used commonly in the LSU Chemical Engineering curriculum because it offers an approach to process modeling that is quicker and more realistic than typical written calculations. At the beginning of the semester, students are tasked with familiarizing themselves with the type of manufacturing process chosen. This is usually accomplished through analyzing literature detailing the importance of the process, available commercial processes, safety concerns, and design considerations. Students also calculate the required feed rate for the desired product production rate so this can be later implemented in their Aspen Plus simulation.

Throughout the semester, more challenging topics are covered that are appropriate to the level of the design and offer additional opportunity for optimization.

As well as completing quizzes and recitations, each team submits three reports. The first progress report for the Fall 2022 offering of CHE 4172 was due on October 17th, 2022. This report consists of the basics of the design. Here, students are tasked with completing an operating, error-free process design that meets the desired product purity specification and overall reactant conversion. Waste disposal costs and by-product credits should also be evaluated in this report. For this report, students complete an economic assessment which assesses aspects of the design such as the raw material cost, the total capital investment (TCI), utility costs, and yearly product sales. A discounted cash flow table is used to determine the product price. For the second report, more thorough design is needed in order to decrease the capital cost and offer a more competitive product price. Students explore design alternatives to improve the profitability of their system—hoping to offer the product at a more competitive price. A safety analysis is also completed on the design for the final report.

As a component of the economic analysis, a capital cost assessment is conducted to determine the TCI of the designed process. The TCI includes all of the costs to build a new facility, such as the costs for equipment purchase and installation, spare equipment costs, initial catalyst costs, costs for plant startup, and working capital. [5] Historically, the capital cost assessment has been completed using LSU Professor Armando Corripio's Equipment Costs Excel Spreadsheet. This spreadsheet includes cost calculations for trayed columns, packed columns, heat transfer equipment, vessels, reactors, compressors, expanders, and pumps. The spreadsheet utilizes calculations from *Product and Process Design Principles by Seider, W.D., Seader, J.D., Lewin, D.R., and Wildago, S.; Conceptual Design of Chemical Processes by J.M. Douglas, and Capital Cost Estimating by K.M. Guthrie.* [6] Students use the costs calculated from this spreadsheet in their intermediate progress reports, final report, and final presentation. In the semesters preceding Fall 2022, students and faculty often received feedback from the industrial judges that the equipment costs and therefor capital cost assessments were largely undervalued—often times as much as 10 times less than industry values. This problem has continued to progress as there is no intermediate feedback from industry professionals to aid students in fixing their capital cost assessments prior to the final presentation. Due to the competitive nature of the industry, prices for similar equipment are rarely or never available online for students to access and include in their assessments. These two situations hinder students from checking their capital costs assessments prior to the final presentation.

Aspen Plus V12 APEA software is a viable alternative to the traditional spreadsheet method that has been used. The APEA software easily calculates equipment and utility costs and indexes them to the current year. [3] During the Fall 2022 semester, the CHE 4172 utilized this method to calculate the capital costs for their design projects. This thesis will evaluate the differences in the two capital cost assessment methods—Method 1: Aspen APEA Economic Analysis and Method 2: Equipment Costs Excel Spreadsheet. It is expected that Method 1: Aspen APEA Economic Analysis will give a more appropriate capital cost assessment due to its rigorous sizing ability, individualized material specification factors, and updated information database. The *Product and Process Design Principles* text provides additional reasoning as to why one should expect Method 1 to provide better cost estimates. It concludes that Method 1 will provide more accurate estimates as Method 2's cost estimates are based on correlations formulated from data that is only accurate to $\pm$25%. [5] Providing students with a tool that provides accurate capital cost assessments is crucial as it will allow them to produce an accurate economic analysis for their process designs. Furthermore, when students produce accurate capital cost assessments they will complete their senior-level courses with the confidence and understanding to recognize feasible capital cost assessment values. Providing accurate cost assessments is crucial as it allows industry judges to be confident in LSU's ability to produce competent chemical engineers. Recommendations will be provided as to which method will be best to move forward with in future semesters.

Chapter 2: The Manufacturing Process Designed During the Fall 2022 Semester Produced Styrene Monomer.

For the Fall 2022 semester, LSU CHE 4172 students designed a styrene monomer manufacturing process. As described in the Project 1 Assignment Document, the styrene is to be provided to a hypothetical polystyrene unit within the same facility. [3] Styrene is an important product in the chemical industry and is most commonly found in plastics. [8] Styrene is crucial in the production of "polystyrene, ABS, SAN, styrene–butadiene latex, SBR, and unsaturated polyester resins." [7] Styrene possesses many qualities that make it desirable such as its colorlessness, stability, and low cost. [8] Commercial processes for styrene were developed in the 1930s, but World War II sparked the large-scale production of styrene due to the large amounts of styrene-butadiene rubber needed to support the war efforts. [8] Styrene production has been steadily increasing since then with significant demand in South America, Eastern Europe, and the Middle East. [7] A styrene molecule is shown in **Figure 1** and contains a benzene ring and is made entirely of carbon and hydrogen atoms. [9]

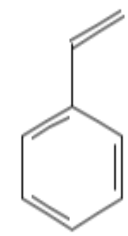


Figure 1. Molecular Structure of a Styrene Molecule: This figure was reproduced from the National Center for Biotechnology Information. [9]

$$EBZ \leftrightharpoons STY + H_2 \qquad \text{Rxn. (1)}$$
$$EBZ \rightarrow BZ + C= \qquad \text{Rxn. (2)}$$
$$EBZ + H_2 \rightarrow TOL + CH_4 \qquad \text{Rxn. (3)}$$

Styrene is produced from a feed of ethylbenzene (EBZ) by three reactions. The first reaction produces the product, styrene (STY), and hydrogen (H_2). [3] Two side reactions (rxns. 2 and 3) produce by-products benzene (BZ), ethylene (C=), toluene (TOL), and methane (CH_4). [3] The design will be optimized to achieve an EBZ conversion of 65% while reducing the amount of by-products produced. [3] STY is produced as the main product, but there is opportunity to utilize some by-products advantageously.

Economics

Designing a chemical manufacturing plant requires exploring every option to save money and increase profits while also accounting for safety and environmental protection. The prices for feed, product, and by-products as given in the Project 1 Assignment Document are shown in **Table 1.** [3] The polystyrene facility to which the styrene is provided currently purchases their styrene from another supplier for 0.70 $ per pound. [3] The objective of the process design project was to design a process that can offer styrene at a more competitive price. The purchase price of EBZ and injection steam is also shown in **Table 1.** As specified in the Project 1 Assignment Document, unpurified hydrogen can be sold as a by-product and combustible gas wastes (containing only carbon, hydrogen, and oxygen) can be sent to an on-site steam boiler in exchange for a fuel credit. [3] Any waste streams containing greater than 10 weight% water must be disposed of properly, incurring a cost that is a combination of the waste water processing, organic separations, and organic disposal costs. [3] As shown in **Table 2,** there are twelve utilities that can be used to

Chemical Species:	Price:
Styrene	0.70 $/lb
Ethylbenzene	0.55 $/lb
Injection Steam	0.004 $/lb
Hydrogen	4.00 $/1000 SCF
Combustible Gas Wastes	Fuel Gas Credit
Waste Water Processing Cost	41$ / 1000 m3
Organic Separations Cost	0.15 $/lb
Organic Disposal Cost	3.51 $/GJ

Table 1. Economic Costs for the Styrene Process. This data in this table was reproduced from the Project 1 Assignment Document. [3]

operate the equipment. The most economical utility that will achieve the objective should be chosen to lessen overall utility costs for the proposed process. An Aspen simulation must be completed for the process prior to economic evaluation. Details of the Aspen process design simulation will be described in the next two sections and the economic evaluation will be presented in Chapter 3.

Cost and Properties of Utilities				
	Aspen Naming:	Inlet conditions	Outlet conditions	$/MMBtu
Steam	STM610	610 psia, vapor fr. = 1	610 psia, vapor fr. = 0	6.20
Steam	STM160	160 psia, vapor fr. = 1	160 psia, vapor fr. = 0	4.00
Steam	STM25	25 psia, vapor fr. = 1	25 psia, vapor fr. = 0	2.40
Cooling Water	CW20	80ºF, 35 psia	100ºF, 25 psia	0.18
Cooling Water	CW10	80ºF, 35 psia	90ºF, 25 psia	0.36
Cooling Water	CW5	80ºF, 35 psia	85ºF, 25 psia	0.72
Cooling Water	CHILL	40ºF, vapor fr. = 0	45ºF, vapor fr. = 0	17
Refrigeration	R-150	-150ºF, vapor fr. = 0	-150ºF, vapor fr. = 1	148
Refrigeration	R-30	-30ºF, vapor fr. = 0	-30ºF, vapor fr. = 1	45
Furnace Heat	FURNACE	1800ºF, vapor fr. = 1	1500ºF, vapor fr. = 1	4.50
Electricity	Elect	$0.070/kW-hr		
Fuel	Gas	$4.00/MMBTU		

Table 2. Utility Costs and Properties for the Styrene Process. This table was reproduced from the Report 1 Assignment supplied by Mr. Guillory to the CHE 4172 class. [3]

The Process

The styrene process as modeled in Aspen is shown in **Figure 3.** The process consists of two mixers, two plug flow tubular catalytic (PFTR) reactors, one flash drum, two pumps, two compressors, two distillation columns, three furnaces, three heaters/coolers, and two HeatX heat exchangers. The annual production rate of styrene is 525,742 metric tons/year which requires 559,338 metric tons/year EBZ and 186,244 metric tons/year of high-pressure injection steam. Unreacted EBZ is recycled to decrease raw material costs to the system. A mixer (MMEIF) is used to mix the recycled and fresh EBZ. The injection steam is mixed with the fresh and recycled EBZ feed in another mixer (ME1F). The injection steam works to heat the feed to achieve the intended conversion. The mixed streams then pass through a heater (E1XA), a heatX heat exchanger (E13X), and a furnace (E1XB) in order to be heated to a high enough temperature prior to entering the reactors. The EBZ is then reacted in two reactors (R1 and R2) to produce styrene and other by-

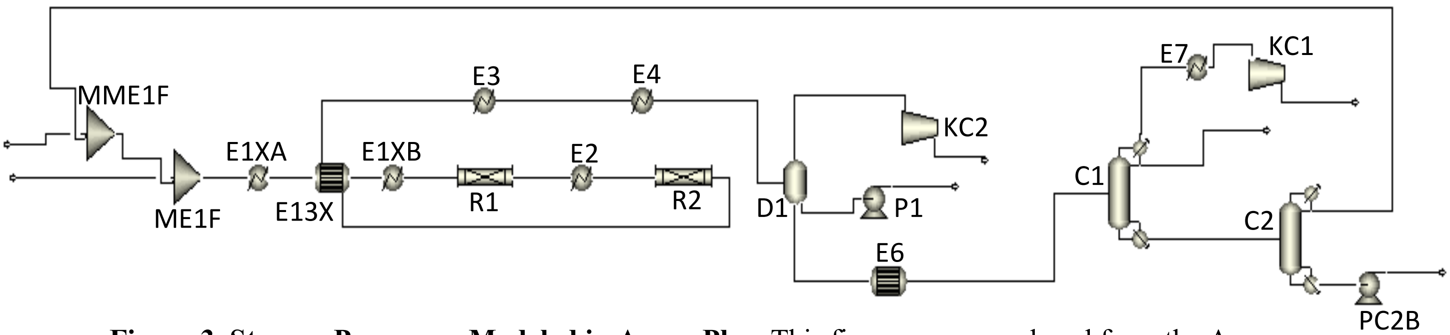


Figure 3. Styrene Process as Modeled in Aspen Plus. This figure was reproduced from the Aspen simulation created by our team.

products. E2 is an intermediate furnace that heats the stream to reach the desired EBZ conversion in R2. The outlet of the second reactor is then cross-exchanged with the inlet to the reactors for cooling. Two more heat exchangers (E3 and E4) are used to cool this stream prior to entering the flash drum (D1). D1 is used to separate the lighter components (H_2, $C =$, and CH_4) from the other components. The lighter components are sent to an on-site steam boiler for a fuel gas credit which requires them to leave the process at greater than or equal to 25 psia in order to gain the fuel credit. [3] A compressor is shown on this stream (KC2) that is not necessary for the process as the stream is at 30 psia. This is included for capital cost comparison carried out in this thesis because preliminary results indicated that Method 2 may not correctly cost compressors of smaller and larger sizes (data not shown). Water is also separated from the other components in D1 and is treated as waste water. A pump (P1) is not necessary for this stream but is included for capital cost comparison purposes. This additional analysis is necessary because pumps and compressors are sized similarly in Method 2 and there is reason to believe that Method 2 may also incorrectly cost pumps of smaller and larger sizes. The bottom stream from D1 (D1B) contains mainly STY, EBZ, TOL, and BZ. This stream is heated in heat exchanger E6 and is then sent to the first column (C1). In C1, TOL and EBZ are the light and heavy components, respectively. A majority of the TOL and BZ are produced in the distillate of C1 while the STY and EBZ are sent to the second column (C2). The distillate of C1 is heated and compressed in order to be sent to the on-site steam boiler for a fuel credit. C2 separates EBZ and STY with EBZ leaving in the distillate to be recycled as feed. A pump is utilized on the bottoms of C2 to achieve the appropriate pressure prior to being sold as product. The subsequent section will offer more detailed analysis of the process used to design each type of equipment in the Aspen simulation. Pertinent technical details, including design assumptions, will also be provided.

Detailed Design

The purpose of this section is to detail the design processes for each type of equipment and present some of the important technical aspects of the design. This section will discuss how each piece of equipment was designed in the Aspen software.

Reactors-R1, R2

The adiabatic, catalytic, PFTR reactors are designed to reach a 65% conversion of EBZ overall, and 35% EBZ conversion in the first reactor. [3] The reactor diameter for each reactor is specified (6 ft), but the Aspen Plus Design Specification tool (commonly known as a design spec) is utilized for each reactor to determine the reactor length needed to reach the intended conversion. [3]

Further analysis is completed with a sensitivity analysis for each reactor. Each sensitivity analysis varies the pressure and temperature in each reactor. This works with the design specs to determine the optimal reactor length for each temperature and pressure combination. Reactors should be designed to have a length less than 50 feet, so the user chooses the best temperature and pressure from the sensitivity analysis results that meets this criteria. [3] The reactor pressure is set to this selected pressure and the heat exchanger, prior to each reactor, heats the inlet to the selected temperature. The reactor pressures, lengths, and inlet temperatures are shown in **Table 3.**

Reactor	Inlet Temperature (°F)	Reactor Pressure (psia)	Reactor Length (ft)
R1	1142.2	3.4	38.2
R2	1200.0	3.0	47.8

Table 3: Designed Characteristics for Reactor Blocks in Aspen Plus. The data in this table was collected from the Aspen simulation created by our team.

Distillation Columns-C1, C2

Designing distillation columns in Aspen is most easily begun by using DSTWU blocks. A DSTWU block is a shortcut distillation modeling method that uses the Winn, Underwood, and Gilliland correlations to provide the user with details for more rigorous design. [10] DSTWU blocks can only be used for columns with one feed stream and two product streams. [10] The user inputs the heavy key component, light key component, and desired purities. A -1.2 reflux ratio is chosen as an initial value in Aspen where the -1.2 reflux ratio indicates a reflux ratio 1.2 times the minimum reflux ratio. Condenser and reboiler pressures are also chosen. The DSTWU is simulated with the results including the number of stages, actual reflux ratio, distillate to feed (DtoF) ratio, and feed stage among others. These results are transferred to a RadFrac block for more rigorous design as Radfrac blocks utilize rigorous fractionation calculations for rating and design. [10] Design specs are added to the RadFrac block to specify the purities for the heavy and light key components. Once the intended purities are achieved, the Aspen Column Internals tool is used to specify the tray or packing type, column diameter, and other internal column specifications. The Aspen Auto Section tool is used to section the column. Column parameters are adjusted until the hydraulic plots across the column are completed without errors or warnings. As shown in **Figure 4,** a column which has internals that are hydraulically suitable will show all stages as blue. This approach was used to design each of the distillation columns with column 1 being designed prior to column 2.

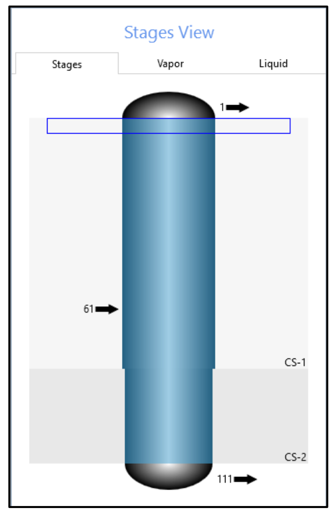


Figure 4 Aspen Hydraulic Analysis of Column 2 Internals. This figure was reproduced from the Aspen Plus model created by our team.

Column	Reflux Ratio	DtoF Ratio	Number of Stages	Feed Stage	Condenser Pressure (psia)	Reboiler Pressure (psia)
C1	112.7	0.007	23	11	7	26
C2	20.0	0.343	111	61	15	21

Table 4: Designed Characteristics for Distillation Columns in Aspen Plus. The data in this table was collected from the Aspen simulation created by our team.

The designed parameters for both distillation columns are displayed in **Table 4.** Both columns 1 and 2 are designed as trayed columns with sieve trays. Each column has two sections. The overall tray efficiency is chosen as 70% and the tray spacing for each section is chosen as 2 ft. [3] Other characteristics of the column internals are displayed in **Table 5.** Both columns utilize the CW20 utility in the condenser and the STM160 utility in the reboiler to achieve the appropriate reflux and boilup rates.

Column	Section	Start Stage	End Stage	Number of Passes	Diameter (ft)
C1	1	2	10	1	23.4
	2	11	22	2	17.1
C2	1	2	80	2	21.9
	2	81	110	2	20.7

Table 5: Designed Column Internals for Distillation Columns in Aspen Plus. The data in this table was collected from the Aspen simulation created by our team.

Pumps-P1, PC2B

Pump design in Aspen is completed by choosing the desired discharge pressure of the pump. P1 discharges at 220 psia and PC2B discharges at 25 psia. All pumps are assumed to have 80% pump efficiency and 95% driver efficiency. [3] These efficiencies are included in the Aspen pump design. All pumps use the ELECT utility.

Compressors-KC1, KC2

Compressors are designed similarly to pumps needing only the discharge pressure to be specified. KC1 discharges at 25 psia and KC2 discharges at 250 psia. All compressors are assumed to have 80% polytropic efficiency and 95% mechanical efficiency. [3] These efficiencies are included in the Aspen compressor design. All pumps use the ELECT utility.

Flash Drums-D1

A flash drum (D1) is used to separate the water and lighter components from the STY, EBZ, TOL, and BZ. H_2 is the main component being removed from the drum and it can be sold as a by-product without purification. Since purification is not necessary, distillation is not required and therefore a flash drum can achieve the needed separation at a much lower cost. The flash drum is operated at 85 ºF and 30 psia and there is no pressure drop across the flash drum. The flash drum is assumed to be 50% full of liquid at any time. [3] The residence time cannot be inputted directly into the Aspen Flash Drum block, but it is utilized in both equipment costing methods. Consistent with the default in Aspen APEA, the flash drum is chosen to have a residence time of 5 minutes.

Furnaces-E2, E1XB, E7

There are three furnaces in the styrene process, E2, E1XB, and E7. Furnaces are utilized when

Exchanger	Inlet Temperature (°F)	Outlet Temperature (°F)	Pressure (psia)
E2	912.0	1200.0	2.4
E1XB	891.0	1142.0	3.3
E7	128.0	200.0	7.0

Table 6: Designed Characteristics for Furnaces in Aspen Plus. The data in this table was collected from the Aspen simulation created by our team.

heating at high temperatures is needed or when temperature crossover is a concern. Furnaces are simple to design as only the outlet temperature and pressure need to be specified. The designed outlet temperatures and pressures are shown in **Table 6.** The furnaces are modeled as heater blocks in Aspen and use the FURNACE utility. E7 and E1XB are modeled as furnaces due to their high temperatures. These furnaces are vital as they ensure that the stream reaches the correct temperature prior to entering the reactors so the appropriate conversions can be achieved. E7 is designed as a furnace so it can achieve the desired outlet temperature without creating any pressure drop. E7 is essential as it heats up the stream to KC1 so this stream can be properly pressurized prior to being sold for a fuel gas credit.

Heaters/Coolers-E1XA, E3, E4

There is one heater, E1XA, and two coolers, E3 and E4, in the styrene process. These heaters/coolers must have straight heat duty-temperature (TQ) curves. [3] The heaters/coolers are designed exactly like the furnaces with only the outlet temperature and pressure needing to be specified. There is one additional step when designing heaters and coolers. After the inputs are specified, the Hcurves tool in Aspen should be used to populate the TQ curves to determine their linearity. If the TQ curve is like **Figure 5,** the heater/cooler needs to be separated into two separate Aspen heater blocks with the first exchanger's outlet temperature designated as the temperature at which the two separate slopes meet (**Figure 5**, red circle). The two new heater/coolers should have TQ curves like **Figure 6.** The inlet/outlet temperatures, pressures, and utilities of each of the

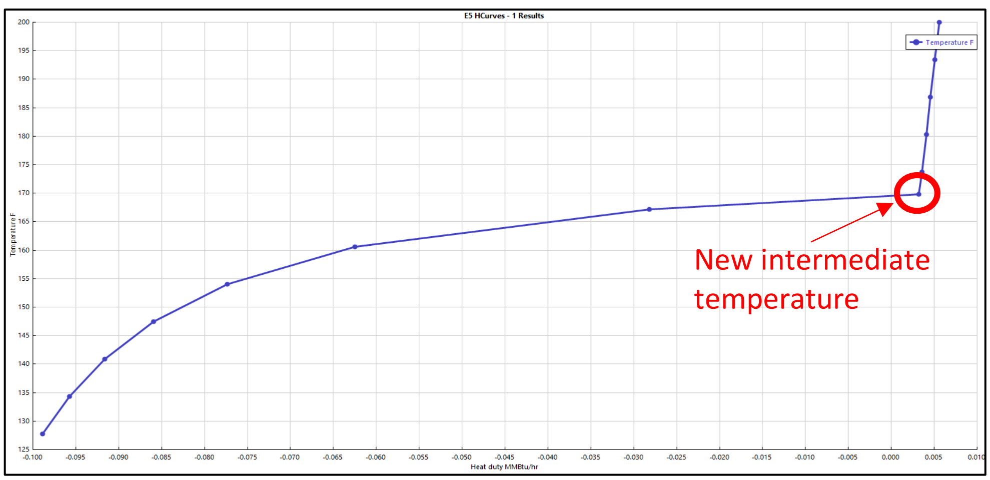


Figure 5. Example of a Non-linear TQ Curve. This figure was reproduced from the Aspen Plus simulation created by our team.

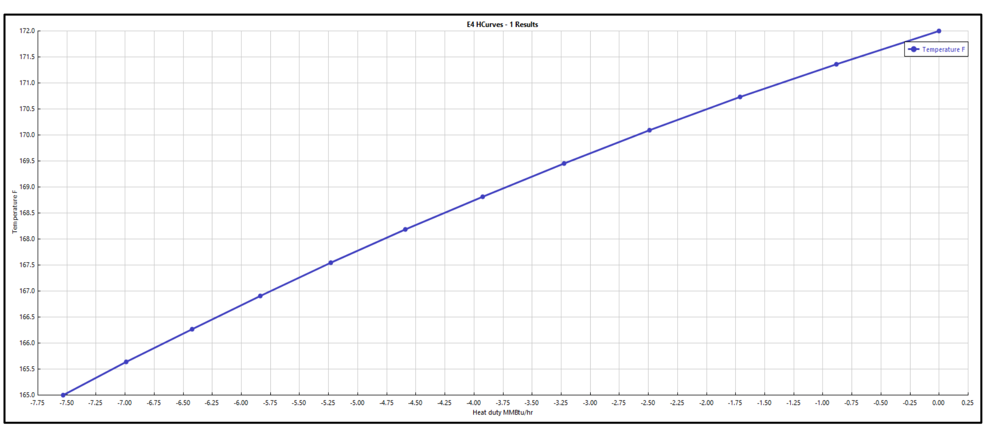


Figure 6. Example of a Linear TQ Curve. This figure was reproduced from the Aspen Plus simulation created by our team.

heaters and coolers are presented in **Table 7.** The least costly utility should be chosen that can accomplish the needed heat transfer.

Exchanger	Inlet Temperature (°F)	Outlet Temperature (°F)	Pressure (psia)	Utility
E1XA	170.0	200.0	15.0	STM160
E3	230.0	172.0	30.0	CW10
E4	172.0	165.0	30.0	CW20

Table 7: Designed Characteristics for Heaters and Coolers in Aspen Plus. The data in this table was collected from the Aspen simulation created by our team.

HeatX Heat Exchangers-E6, E13X

HeatX heat exchanger blocks provide a more rigorous approach to heat transfer because they can estimate sensible heat and fouling factors. [10] Two HeatX blocks are used in the process, E6 and E13X. Not only can HeatX blocks appropriately handle non-linear TQ curves, but HeatX blocks can be used for cross exchange. Cross exchangers are a valuable resource that can save money in utility and capital costs. Designing HeatX blocks requires more inputs than heaters, coolers, and furnaces. When used in shortcut mode, the user specifies the hot inlet-cold outlet temperature difference and the minimum temperature approach. The minimum temperature approach for all HeatX blocks in the styrene process is 10 °F. [3] A constant overall heat transfer coefficient (Uo) is also entered. E13X uses a Uo of 153.8 Btu/hr-sqft-R while E6 uses a Uo of 40.8 Btu/hr-sqft-R. These values are estimated by the user based on the characteristics of the streams. E6 uses STM160 as the hot utility. The cold-side fluid is vaporized; the inlet temperature is 85 °F and the exit temperature is 344 °F. E6 was modeled as a HeatX exchanger due to the vaporization that occurs. E13X is a cross-exchanger. The cold-side fluid is heated from 200 °F to 891 °F; it enters as a vapor-liquid mixture and it is completely vaporized in the exchanger. The hot-side enters as a vapor at 1008 °F and exits as a vapor at 230 °F. HeatX blocks have the potential for very in-depth design, having many options relating to exchanger geometry.

Chapter 3: A Capital Cost Assessment Comparison Was Completed to Determine the Best Method to Use in Future Semesters.

A capital cost assessment is a crucial part of a manufacturing process design. This study will compare two distinct capital cost assessment methods—Method 1: Aspen APEA Economic Analysis and Method 2: Equipment Costs Excel Spreadsheet analysis. Capital cost assessments entail various aspects of economic analysis, but the calculated sum of the installed costs of the equipment is indicative of which capital cost assessment method is the most feasible. Therefore, this thesis will compare the calculated installed equipment costs using each method. Method 1 computes installed equipment costs that are indexed to the current year, 2022 [3]. These values are displayed in USD ($). It utilizes data directly from the Aspen simulation to calculate the installed costs. The APEA tool automatically chooses to map each piece of equipment to a predesigned format. Items can be remapped if different analysis is needed. Method 2 uses a CE inflation index—or Chemical Engineering Plant Cost Index—factor to index equipment cost values to the current year. [5] CE inflation index values are not widely published, but CPI values are. Since they can be assumed to follow the same trend, CPI values are used to proportionally determine the CE inflation index for 2022. *Product and Process Design Principles: Synthesis, Analysis and Evaluation* gives the most recent economic values from 2013; the CPI value is 233 and the CE inflation index is 567. [5] The CPI index in September 2022 was 296.808. [11] This is proportional to a CE inflation index value of 722.275. Method 2 is relatively simple to use—it requires the user to model the equipment as a block in Aspen and use some of the results as inputs in the spreadsheet. Method 2 uses correlations based on published equipment cost data. [5] These correlations use a size factor that is unique to each type of equipment to determine the basic purchase cost of the equipment. [5] The inputs required for these size factors may be heat duty, temperature, column diameter, etc. depending on the type of equipment. Often factors are used for material type, design type, design pressure, etc. [6] These factors are included in the spreadsheet. The base correlation is based on common material specifications and equipment designs so these additional design factors are used to adjust the base equipment cost for unique materials or equipment designs. [5] Method 2 reports installed costs in thousand USD (k$) so each value will be multiplied by 1000 for comparison with the Method 1 values. Seven types of equipment were studied for capital cost comparison—compressors, pumps, flash drums, heaters, HeatX heat exchangers, furnaces, and distillation columns as described above. A recommendation regarding which method should be used will be given for each type of equipment along with any other ancillary recommendations that are discovered during the comparison. Two types of equipment shown in **Figure 3** will not be economically evaluated in this study—mixers and reactors. While mixers are shown as individual blocks in Aspen, they do not represent physical equipment but rather the mixing of two streams in piping. The reactors will not be evaluated due to the complexity of reactor sizing and evaluation. Each reactor is unique and due to the various types of reactors, costing one type of reactor would not be representative of either method's ability to effectively cost all reactors.

Type 1: Compressors

Compressors are some of the easiest equipment to evaluate economically using either method. The styrene process requires one compressor—KC1—to ensure the gases from C1 exit the system at a pressure greater than 25 psia. Another compressor was added to the system to study how the different methods analyze compressors of different sizes. This compressor is KC2 and is responsible for raising the pressure of the D1 vapor stream to 250 psia. Using Method 1, APEA automatically maps KC1 and KC2 to DGC CENTRIF- horizontal centrifugal compressors. The driver power, gas flow inlet rate, temperature, pressure, and other factors are utilized from the Aspen simulation to calculate the installed cost, as shown in **Figure 7**. The user need only to specify the driver type for the compressor—here MOTOR is chosen. For this comparison, the casing material selection is not pertinent, but the option is available if needed. Using Method 2, both compressors are modeled by entering their total powers, in horsepower (HP),

User tag number	KC1	KC2
Remarks 1	Equipment mapped from 'KC1'.	Equipment mapped from 'KC2'.
Quoted cost per item [USD]		
Currency unit for matl cost		
Number of identical items		
Installation option		
Casing material	CS	CS
Actual gas flow rate Inlet [cuft/hr]	7541.34	280686
Design gauge pressure Inlet [psig]	-7.69652	15.3035
Design temperature Inlet [F]	200	85
Design temperature Outlet [F]	392.093	668.611
Design gauge pressure Outlet [psig]	10.3035	235.303
Compressor speed [rpm]		
Driver power [hp]	6.66023	2293.41
Molecular weight	28.9066	2.99726
Specific heat ratio	1.20791	1.39245
Compressibility factor Inlet	0.995355	1.00079
Compressibility factor Outlet	0.991696	1.00564
Intercooler required		
Intercooler type		
Aftercooler required		
Aftercooler type		
Inter/Aftercooler excess area [Percent]		
Interstage pressure drop [psig]		
Driver type	MOTOR	MOTOR
Turbine gauge pressure [psig]		
Lube oil system		
Allow resize		

Figure 7. Method 1 Analysis for Compressors. This figure was reproduced from the APEA evaluation tool on the Aspen Plus simulation created by our team.

and compressor type factors. Both of these compressors are assumed to be centrifugal compressors with motor drivers, so a design type factor of 1 is used. These calculations can be found in **Figure 8**. As shown in **Table 8**, the smaller compressor, KC1 (6.6 HP), is highly undervalued by Method 2 by as much as 90.7%. This is most likely because this compressor's total power value is lower than the range of total power values Method 2's centrifugal compressor correlation is designed for. KC1 has a total power of 6.6 HP while Method 2 is only designed to estimate costs for centrifugal compressors that have total power values in the range of 200-30,000 HP. [5] Method 2 overvalues

Compressors						
Aspen+ block label	KC1	KC2	Sample	Sample		Total HP from Aspen+ results. Specify efficiency.
Total power, hp	6.66023	2293.41	2000	2000	<--	If multistage, total power of all stages
Compressor type factor	1.00	1.00	1.00	1.00		
Compr. Installed Cost, k$	86	3,394	3,114	3,114		

Design Type Factors	
Type	Factor
Centrifugal, motor	1.00
Reciprocating, turbine	1.07
Centrifugal, turbine	1.15
Reciprocating, motor	1.29
Reciprocating, gas tbn	1.82

Ref: Seider, W.D., Seader, J.D., Lewin, D.R., and Widagdo, S., *Product and Process Design Principles*, 4th ed., **Wiley**.
(Added 1.15 factor for the installation cost.)

Ref: J.M. Douglas, *Conceptual Design of Chemical Processes*, **McGraw-Hill, 1988**, Appendix E, pp.568-577.
Based on correlations by K.M. Guthrie, *Capital Cost Estimating*, **Chem. Eng., 76**(6):March 24, 1969, p. 114,

Figure 8. Method 2 Analysis for Compressors. This figure was reproduced from the Equipment Costs Excel Spreadsheet utilizing values from the Aspen Plus simulation created by our team. [6]

Equipment Name	Installed Cost Method 1 [USD]	Installed Cost Method 2 [USD]	Over/Under Evaluation (%)
KC1	$926,000	$86,000	-90.7%
KC2	$2,156,000	$3,394,000	+57.4%

Table 8: Installed Cost Comparison for Compressors. This table was creating using data from both the Aspen APEA Economic Analysis Tool and the Equipment Costs Excel Spreadsheet.

the larger compressor, KC2 (2293.4 HP), by 57.4%. From this data, the conclusion is that Method 2 is inconsistent for compressors of different sizes. **Therefore, the recommendation for estimating the installed cost for compressors is to use Method 1: Aspen APEA.** This option is optimal because not only does it provide the most reasonable estimate, it is the easiest to use. In order for Method 2 to be effective for compressors of all sizes, additional factors would need to be calculated and implemented for compressors of small and large sizes.

Type 2: Pumps

Pumps are modeled similarly to compressors, needing very few user inputs for either method. There is only one pump needed for the styrene process—pump PC2B. This pump is used to ensure the bottoms stream of C2 leaves the system at a pressure greater than 25 psia (similarly to KC1). This pump is relatively small, compared to P1, as it only needs to raise the pressure of the stream by 4 psi. Another pump was added to the system to study how the different methods analyze pumps of different sizes. This pump was P1 and was responsible for raising the pressure on the water stream from the flash drum (D1) by 190 psi. C1 and C2 are reflux pumps that are also shown in **Figure 9** which will be addressed later when costing the distillation columns. The liquid flow, pressure rise, and liquid density are used to calculate the fluid head, power, and installed cost of PC2B and P1. An efficiency of 80% is used for both methods. [3] Comparing the fluid heads for PC2B and P1 in **Figures 9 and 10**, it is obvious that both methods use a similar process to calculate the fluid head. Method 1 automatically maps the pumps to DCP CENTRF—a centrifugal single or

User tag number	C2-reflux pump	PC2B	C1-reflux pump	P1
Remarks 1	Equipment mapped from 'C2'.	Equipment mapped from 'PC2B'.	Equipment mapped from 'C1'.	Equipment mapped from 'P1'.
Quoted cost per item [USD]				
Currency unit for matl cost				
Number of identical items				
Installation option				
Casing material	CI	CI	CI	CI
Liquid flow rate [cuft/hr]	22250.9	3019.28	13355	823.274
Fluid head [ft]		11.9767		443.565
Speed [rpm]				
Fluid specific gravity	0.75967	0.771471	0.8451	0.989447
Driver power [hp]				
Driver type	MOTOR	MOTOR	MOTOR	MOTOR
Seal type				
Design gauge pressure [psig]	15.0005	35.3052	15.0005	230.304
Design temperature [F]	328.615	369.273	250	250
Fluid viscosity [cP]	0.5	0.5	0.5	0.5
Pump efficiency [percent]	70	80	70	80
Allow resize		No		Yes

Figure 9. Method 1 Analysis for Pumps. This figure was reproduced from the APEA evaluation tool on the Aspen Plus simulation created by our team.

Centrifugal Pumps					
Flow, ft3/hr	3019.3	823.3	1227.0	1227.0	1227.0
Pressure rise, psi	4	190	1	385	385
Liquid density, lb/ft3	48.14	61.74	4.83	64.83	64.83
Q, gpm	376.4	102.6	153.0	153.0	153.0
H (head), ft-lbf/lb	12.0	443.1	29.8	855.2	855.2
S = Flow*sqrt(Head)	1302	2161	835	4473	4473
Material factor	1	1	1.35	1.35	1.35
Pump type	1	1	2	2	2
Type factor	2.075	1.971	5.309	2.306	2.306
Installed cost, k$/pump	10.3	10.9	21.8	16.5	16.5
Power, hp (80% eff,)	1.1	14.2	0.1	42.9	42.9
Electric motor type	1	1	3	3	3
Motor cost, k$	0.2	1.6	0.1	5.6	5.6
Pump & motor, k$	10.5	12.6	21.9	22.1	22.1
Installed spare, k$	10.5	12.6	21.9	22.1	22.1
Total istalled cost, k$	21	25	44	44	44

Pump material factors	
Material	Factor
Ductile iron	1.00
Cast steel	1.35
Stainless steel	2.00
Monel	3.30
Titanium	9.70
Hastelloy C	2.95
Bronze	1.90

Pump type		Qmax, gpm	Hmax, ft-lbf/lb
1	One stage	1500	450
2	Two stage	1200	1100
3	Multistage	1500	3200

Motor type		Max hp
1	Enclosed, fan cooled	250
2	Enclosed, fan cooled	400
3	Explosion-proof	200

Figure 10. Method 2 Analysis for Pumps. This figure was reproduced from the Equipment Costs Excel Spreadsheet utilizing values from the Aspen Plus simulation created by our team. [6]

multi-stage pump. User inputs for Method 1 include the casing material, here cast iron (CI) is used, and driver type, MOTOR is chosen. For Method 2, the material factor is chosen as 1 for ductile iron and the pump type design factor is chosen as 1 for a single stage pump based on volumetric flow and fluid head. While Method 1 only allows the user to specify the driver type as MOTOR, Method 2 allows the user to decide between different types of motors as shown in **Figure 10.** For PC2B and P1, the electric motor type factor is chosen as 1 for an enclosed, fan cooled motor. While the base options for the pumps are the same across the methods, Method 2 does offer a more individualized approach with more extensive pump and motor options.

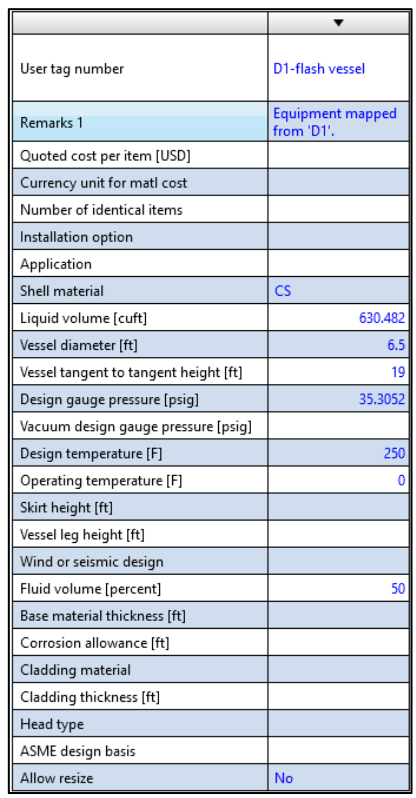
Equipment Name	Installed Cost Method 1 [USD]	Installed Cost Method 2 [USD]	Over/Under Evaluation (%)
PC2B	$54,100	$21,000	-61.2%
P1	$58,500	$23,000	-60.7%

Table 9: Installed Cost Comparison for Pumps. This table was creating using data from both the Aspen APEA Economic Analysis Tool and the Equipment Costs Excel Spreadsheet.

As shown in **Table 9**, regardless of the size of the pump, Method 2 undervalues installed costs of the pumps. P1 requires 14 times the power of PC2B and has a pressure rise that is 47.5 times greater than PC2B. P1 does have a lesser volumetric flow, but its fluid head is nearly 37 times as large as PC2B. Regardless, Method 2 undervalues each pump by approximately 60%. Since it is evident that both methods calculate the fluid head in the same manner, it can be concluded that the difference in installed costs is not due to this calculation. Due to the similarity in the fluid head calculations and the consistency in the difference between the two methods, it can be concluded that the undervaluation by Method 2 is most likely due to outdated costing methods and factors. Since it is known that costs have been undervalued in previous semesters while using Method 2, **the recommendation for estimating the costs of installed pumps is to utilize Method 1: Aspen APEA analysis.** While certain aspects of pump and motor design cannot be chosen with this method, it offers a cost analysis closer to what is expected. This method is also simpler, with only two inputs needed from users. Method 2 includes the cost for a spare pump and motor; it is not evident whether Method 1 includes the price for this spare equipment.

Type 3: Flash Drums

There is only one flash drum needed for the styrene process—D1. The Aspen APEA analysis for D1 is shown in **Figure 11.** Flash drums are automatically mapped to a DVT cylinder, or vertical process vessel in APEA. APEA automatically retrieves the inlet and outlet volumetric flows to calculate the vessel volume. The user need only to specify the material. If a certain fluid volume percent is needed, it can be adjusted here. A 50



User tag number	D1-flash vessel
Remarks 1	Equipment mapped from 'D1'.
Quoted cost per item [USD]	
Currency unit for matl cost	
Number of identical items	
Installation option	
Application	
Shell material	CS
Liquid volume [cuft]	630.482
Vessel diameter [ft]	6.5
Vessel tangent to tangent height [ft]	19
Design gauge pressure [psig]	35.3052
Vacuum design gauge pressure [psig]	
Design temperature [F]	250
Operating temperature [F]	0
Skirt height [ft]	
Vessel leg height [ft]	
Wind or seismic design	
Fluid volume [percent]	50
Base material thickness [ft]	
Corrosion allowance [ft]	
Cladding material	
Cladding thickness [ft]	
Head type	
ASME design basis	
Allow resize	No

Figure 11. Method 1 Analysis for Flash Drums. This figure was reproduced from the APEA evaluation tool on the Aspen Plus simulation created by our team.

Flash drums	
Aspen block label	D1
Liquid outlet flow, ft3/hr	4483.838
Liquid residence time, hr	0.08333
Length-to-diameter ratio	2.923
Liquid volume, ft3	373.6
Vessel volume, ft3	747.3
Vessel diameter, ft	6.879
Vessel length, ft	20.107
Design press. factor	0.00
Material factor	1.00
Cost factor Fc	1.00
Total installed Cost, k$	**169**

Figure 12. Method 2 Analysis for Flash Drums. This figure was reproduced from the Equipment Costs Excel Spreadsheet utilizing values from the Aspen Plus simulation created by our team. [6]

fluid volume percent is chosen for comparison with Method 2 which has a default of 50 fluid volume percent. There are other design options in the interactive sizing tool in the Aspen APEA analysis tool. To determine what default parameters were used by Aspen APEA to size and cost the equipment, the user must first size and evaluate the equipment costs in APEA. Next, the user should change the last row in **Figure 11,** "Allow Resize", to "No", then choose the interactive sizing tool. The default sizing parameters used for the sizing and evaluation will be displayed in the interactive sizing window. The interactive sizing tool for flash drums displays default parameters such as the inlet streams, outlet streams, residence time, diameter, and process vessel height to diameter ratio, amongst others. The default residence time is 5 minutes, or 0.083 hours. The default outlet stream is set to D1B. The calculated capacity using these parameters is also shown in the interactive sizing tool. Changing or adding outlet streams in the interactive sizing tool does not seem to have any effect on the calculated capacity. Method 2 requires a few additional inputs. The liquid volumetric outlet flow can be found by adding the volumetric flows of streams D1B and D1W. The liquid residence time and length-to-diameter ratio are chosen by the user. The appropriate factors are then chosen for a carbon steel vessel that operates at 30 psia. This analysis is shown in **Figure 12.** Comparing the two methods, Method 2 calculates a vessel volume that is roughly 100 cubic feet (ft^3) larger. This discrepancy is most likely due to a difference in how the inlet/outlet flows are used to calculate the liquid volume. While the user can directly enter the outlet flow to be used in Method 2, there is no way to see what flows Method 1 uses to size the vessel. Method 1 boasts a liquid volume nearly twice that of Method 2. A quick calculation reveals that a drum with an outlet flow of 4483.8 ft^3/hr and a residence time of 5 minutes would create a liquid volume of 373.5 ft^3 at any time—the same liquid volume as calculated with Method 2. The reasoning as to why Method 1 calculates a liquid volume nearly two times the expected amount is currently unknown. The differences in calculated liquid

Equipment Name	Installed Cost Method 1 [USD]	Installed Cost Method 2 [USD]	Over/Under Evaluation (%)
D1	$236,600	$169,000	-28.6%

Table 10: Installed Cost Comparison for Flash Drums. This table was creating using data from both the Aspen APEA Economic Analysis Tool and the Equipment Costs Excel Spreadsheet.

volume are apparent in the installed costs for the drum as shown in **Table 10.** While Method 2 does estimate the installed cost as almost 30% lower than Method 1, **the recommendation for costing flash drums is to continue to use Method 2 until a better understanding of Method 1**

User tag number	E1XA	E3	E4
Remarks 1	Equipment mapped	Equipment mapped	Equipment mapped
Quoted cost per item [USD]			
Currency unit for matl cost			
Number of identical items	1	1	1
Installation option			
Heat transfer area [sqft]	2685.28	4226.42	669.852
Number of shells			
Front end TEMA symbol	B	B	B
Shell TEMA symbol	E	E	E
Rear end TEMA symbol	M	M	M
Heat exchanger design option			
Tube material	CS	CS	CS
Tube design gauge pressure [psig]	170.304	0.304011	18.638
Tube design temperature [F]	413.61	280	250
Tube operating temperature [F]	363.61	90	100
Tube outside diameter [ft]	0.0833333	0.0833333	0.0833333
Shell material	CS	CS	CS
Shell design gauge pressure [psig]	108.637	0.304011	35.3052
Shell design temperature [F]	250	280	250
Shell operating temperature [F]	200	230	172
Tube side pipe material			
Shell side pipe material			
Number of tubes per shell			
Tube length extended [ft]	20	20	20
Tube gauge			
Tube pitch [ft]	0.104167	0.104167	0.104167
Shell diameter [ft]			
Shell wall thickness [ft]			
Shell corrosion allowance [ft]			
Expansion joint			
Tube sheet material			
Number of tube passes	1	1	1
Number of shell passes	1	1	1
Allow resize			

Figure 13. Method 1 Analysis for Heaters. This figure was reproduced from the APEA evaluation tool on the Aspen Plus simulation created by our team.

Heaters/Coolers (Straight TQ curves (From Aspen *Heater*, *Results*)			
Aspen block label	E1XA	E3	E4
Heat duty, BTU/h	5.10E+07	-6.65E+07	-7.53E+06
Hot inlet temperature, °F	363.61	230	172
Hot exit temperature, °F	363.61	172	165
Cold inlet temperature, °F	170	80	80
Cold outlet temperature, °F	200	90	100
Uo, BTU/h-ft2-°F	250	200	200
Multipass factor	1	1	1
DeltaTLM, F	178.19	114.32	78.32
Total area required, ft2	1145	2910	481
Number of shells	1	1	1
Area per shell, ft2	1145	2910	481
Material cost factor	1.00	1.00	1.00
Design factor	0.80	0.80	0.80
Pressure factor	0.10	0.00	0.00
Exchanger cost factor	0.90	0.80	0.80
Exch. Installed Cost, k$	**189**	**336**	**104**

Figure 14. Method 2 Analysis for Heaters. This figure was reproduced from the Equipment Costs Excel Spreadsheet utilizing values from the Aspen Plus simulation created by our team. [6]

is gained. Without knowing which flows Method 1 uses to calculate the fluid volume of the flash drum, it is difficult to be confident in Method 1's sizing ability.

Type 4: Heaters and Coolers

Heater blocks (used to model both heaters and coolers) are utilized three places in the styrene process design. These heaters are automatically mapped to TEMA shell and tube exchangers in Method 1. The heat transfer area is calculated in APEA by a set of parameters retrieved from the heater block. Other than choosing the shell and tube side materials, no other user inputs are needed to complete the costing by Method 1. Default parameters related to the sizing of the heat exchangers can be found in the interactive sizing tool in APEA. The interactive sizing tool for heaters displays default parameters such as the overall heat transfer coefficient (U_o), overdesign factor, tube thickness, tube pitch, and tube outside diameter, amongst others. Many of these parameters can be changed by the user if needed. The final surface area calculated by APEA is also shown in the interactive sizing window. As shown in **Figure 14,** costing heaters using Method 2 is more complex. Users must input the heat duty calculated in the Aspen Plus heater block (in BTU/hr), the hot side inlet/outlet temperatures, and the cold side inlet/outlet temperatures. For hot/cold sides where a utility that changes temperature is utilized, it is assumed that the utility completely reaches its exit temperature. A default overall heat transfer coefficient value must be chosen by the user based on the characteristics of the process fluids. There are estimated values from which the user can choose in the Method 2 spreadsheet. Also, material, design, and pressure factors must be selected by the user. Comparing the heat transfer areas calculated by both Methods 1 and 2, it is evident that Method 1 calculates a much greater heat transfer area than does Method 2. This calls into question the heat transfer parameters used in each calculation. It is clear which overall heat transfer coefficients were used in Method 2 as these were user-selected. Determining which overall heat transfer coefficient values were used in

	E1XA		E3		E4	
Method	U_o	HT Area (sqft)	U_o	HT Area (sqft)	U_o	HT Area (sqft)
Method 1-	122.5	2685.3	165.7	4226.4	165.7	669.9
Method 1-	250.0	1316.2	200	3502.1	200.0	555.1
Method 2-	122.5	2335.0	165.7	3511.0	165.7	580.0
Method 2-	250.0	1145.0	200	2910.0	200.0	481.0

Table 11: Comparison of Overall Heat Transfer Coefficients and Calculated Areas. This table was creating using data from both the Aspen APEA Economic Analysis Tool and the Equipment Costs Excel Spreadsheet.

Method 1 is more difficult as Aspen determines the default heat transfer parameters used; these parameters can be located in the interactive sizing tool, as discussed prior. The comparison of the overall heat transfer coefficients chosen by Aspen in Method 1 and the ones selected by the user in Method 2 are displayed in **Table 11**. The user-selected overall heat transfer coefficient values from Method 2 are larger than those selected by Aspen. For comparison, the exchangers will be

Equipment Name	Installed Cost Method 1 [USD]	Installed Cost Method 2 [USD]	Over/Under Evaluation (%)
E1XA	$190,400	$301,000	+58.1%
E3	$201,300	$380,000	+88.8%
E4	$99,500	$118,000	+18.6%

Table 12: Installed Cost Assessment Using Default Heat Transfer Coefficient Values From Aspen. This table was creating using data from both the Aspen APEA Economic Analysis Tool and the Equipment Costs Excel Spreadsheet.

Equipment Name	Installed Cost Method 1 [USD]	Installed Cost Method 2 [USD]	Over/Under Evaluation (%)
E1XA	$136,900	$189,000	+38.1%
E3	$191,400	$336,000	+75.6%
E4	$98,800	$104,000	+5.3%

Table 13: Installed Cost Assessment Using User-chosen Heat Transfer Coefficient Values From the Method 2 Spreadsheet. This table was creating using data from both the Aspen APEA Economic Analysis Tool and the Equipment Costs Excel Spreadsheet.

sized and evaluated using both sets of parameters. The heat transfer areas for each heater block using each analysis method and each method's overall heat transfer coefficient values are shown in **Table 11.** The installed costs for each heater block as calculated using Method 1's overall heat transfer coefficients are shown in **Table 12.** The installed costs for each heater block as calculated using Method 2's overall heat transfer coefficients are shown in **Table 13.** Analysis shows that Method 2 estimates the installed price for the equipment 5-89% higher than Method 1. The installed costs calculated from the two methods have the greatest difference for E3, the exchanger with the largest heat transfer area. When both methods are evaluated with consistent overall heat transfer values, the calculated heat transfer areas are similar. This indicates that both methods are

User tag number	E13X	E6
Remarks 1	Equipment mapped from 'E13X'.	Equipment mapped from 'E6'.
Quoted cost per item [USD]		
Currency unit for matl cost		
Number of identical items	1	1
Installation option		
Heat transfer area [sqft]	10725.9	13728
Number of shells		
Front end TEMA symbol	B	B
Shell TEMA symbol	E	E
Rear end TEMA symbol	M	M
Heat exchanger design option		
Tube material	347S	CS
Tube design gauge pressure [psig]	0.304011	170.304
Tube design temperature [F]	1057.89	413.61
Tube operating temperature [F]	891.248	363.61
Tube outside diameter [ft]	0.0833333	0.0833333
Shell material	SS321	CS
Shell design gauge pressure [psig]	0.304011	108.637
Shell design temperature [F]	1057.89	393.61
Shell operating temperature [F]	1007.89	343.61
Tube side pipe material		
Shell side pipe material		
Number of tubes per shell		
Tube length extended [ft]	20	20
Tube gauge		
Tube pitch [ft]	0.104167	0.104167
Shell diameter [ft]		
Shell wall thickness [ft]		
Shell corrosion allowance [ft]		
Expansion joint		
Tube sheet material		
Number of tube passes	1	1
Number of shell passes	1	1
Allow resize		

Figure 15. Method 1 Analysis for HeatX Heat Exchangers. This figure was reproduced from the APEA evaluation tool on the Aspen Plus simulation created by our team.

accurate in determining the heat transfer area. Method 1 calculates heat transfer areas that are slightly higher which is most likely due to an overdesign factor. An overdesign factor is a contingency factor added to a design calculation to account for uncertainties in a process design. [1] The benefit of using Method 1 in costing heaters and coolers is that a more accurate overall heat transfer coefficient is used for costing. One potential issue with Method 2 is the assumption that each utility fully reaches its potential exit temperature. To determine the actual exit temperature, users would need to do calculations by hand which can be a tedious and confusing process. Users should be discouraged from using heater blocks for several reasons. The costing for heater blocks compared to other types of equipment has the most uncertainty. While Method 1 calculates larger heat trasfer areas in each scenario, its calculated installed prices are consistently less than those using Method 2. This indicates that there is a major discrepancy in the way these costs are calculated. Heater blocks should also be avoided because they are only effective and efficient when their TQ curves are straight. This is a quality often forgotten by users. If heater blocks must be used, **the recommendation for costing heaters and coolers is to use Method 1: Aspen APEA.** A better alternative will be discussed in the next section—HeatX heat exchangers.

Type 5: HeatX Heat Exchangers

HeatX heat exchanger blocks are utilized in two places in the styrene process—prior to the reactors as a cross exchanger (E13X) and on the feed to C1 (E5). HeatX blocks are unique when compared to heater blocks because the block itself calculates the area. This area is then used by both methods to calculate the installed cost for the exchanger. Method 1 maps these cross exchangers to TEMA shell and tube exchangers. As shown in **Figure 15,** the user need only to input the material type for the shell and tubes. The heat transfer area used for the costing in Method 1 is exactly the heat transfer area calculated by the HeatX block without incorporating an overdesign factor in the costing process. As shown in **Figure 16,** Method 2 follows a similar process. The heat transfer area is retrieved from the HeatX block and utilized in the spreadsheet to calculate the installed cost. The user then determines the material, design, and pressure factors. One of the most notable differences in these approaches is

Heat Exchangers (From Aspen *HeatX*, *Thermal Results*,		
Aspen block label	E13X	E6
Total area required, ft2	10726	10176
Number of shells	3	3
Area per shell, ft2	3575	3392
Material cost factor	3.75	1.00
Design factor	0.80	0.80
Pressure factor	0.00	0.10
Exchanger cost factor	3.00	0.90
Exchr. Installed Cost, k$	**1,974**	**1,150**

Figure 16. Method 2 Analysis for HeatX Heat Exchangers. This figure was reproduced from the Equipment Costs Excel Spreadsheet utilizing values from the Aspen Plus simulation created by our team.

the number of shells calculated. Method 2 calculates the number of shells as 3 for both exchangers while Method 1 does not distinguish the number of shells. As shown in **Table 14,** there is a

Equipment Name	Installed Cost Method 1 [USD]	Installed Cost Method 2 [USD]	Over/Under Evaluation (%)
E13X	$684,200	$1,974,000	+188.5%
E6	$431,200	$1,150,000	+166.7%

Table 14: Installed Cost Comparison for HeatX Heat Exchangers. This table was creating using data from both the Aspen APEA Economic Analysis Tool and the Equipment Costs Excel Spreadsheet.

substantial difference in the cost estimates from the two methods. Method 2 calculates an installed cost that is nearly twice as large as the estimate from Method 1. This is most likely due to the number of shells calculated by Method 2. When a heat exchanger sized by Method 1 is specified to have 3 shells, the price is significantly higher—over 1 million USD. Method 2 gives unreasonable estimates for HeatX exchangers, **so the recommendation for costing HeatX heat exchangers is to utilize Method 1.** While this estimate is lower, it is more consistent.

Type 6: Furnaces

There are three furnaces utilized in the styrene process—E2, E7, and E1XB. Prior to cost analysis, these furnaces are modeled as heater blocks in Aspen in order to calculate the heat duty. Since these heater blocks utilize the furnace utility, they must be mapped to a furnace prior to completing costing with Method 1. These furnaces were mapped to EFU BOX—or a box type process furnace. APEA retrieves the standard gas flow rate and duty from the heater block. Users need only to specify the material as shown in **Figure 17.** There are limited costing options for these box type process furnaces—it is not possible to utilize

User tag number	E2	E1XB	E7
Remarks 1	Equipment mapped from 'E2'.	Equipment mapped from 'E1TEST2'.	Equipment mapped from 'E7'.
Quoted cost per item [USD]			
Currency unit for matl cost			
Number of identical items			
Installation option			
Material	321S	321S	CS
Duty [MMBtu/hr]	51.4782	44.2328	0.00624962
Standard gas flow rate [cuft/hr]	3.8699E+07	4.40636E+06	6096.57
Process type	LIQ	LIQ	LIQ
Design gauge pressure [psig]	0.304011	0.304011	0.304011
Design temperature [F]	1250	1192.22	250
Allow resize			

Figure 17. Method 1 Analysis for Furnaces. This figure was reproduced from the APEA evaluation tool on the Aspen Plus simulation created by our team.

Aspen block label	E2	E1XB	E7
Hat duty, BTU/h	4.633E+07	3.981E+07	5.625E+03
Efficiency	0.9	0.9	0.9
Furnace design factor	1	1	1
Material factor	0.75	0.75	0
Pressure factor	0	0	0
Furnace cost factor	1.75	1.75	1
Installed Cost, k$	2,615	2,299	1
Fuel Annual Cost, k$/yr	1,853	1,593	0

Figure 18. Method 2 Analysis for Furnaces. This figure was reproduced from the Equipment Costs Excel Spreadsheet utilizing values from the Aspen Plus simulation created by our team. [6]

interactive sizing on these pieces of equipment. Method 2 is equally as simple, requiring only that the user input the heat duty from the heater block and select the desired cost factors. As shown in **Figure 18,** the costing spreadsheet includes an input for efficiency. The efficiency is used to determine yearly utility costs but it does not affect the installed cost analysis. Comparing the heat duties used in the two cost analysis methods, it is evident that the heat duties utilized by Method 1 are higher than those in Method 2. The heat duties used in Method 2 come directly from the heater block, therefore, Method 1 must use an overdesign factor of roughly 1.1.

Equipment Name	Method 1 Equipment Purchase Cost [USD]	Method 1 Installed Cost [USD]	Method 1 Installation Costs [USD]
E2	$1,902,300	$9,124,300	$7,222,000
E1XB	$1,689,100	$5,638,800	$3,949,700
E7	$12,800	$99,500	$86,700

Table 15: Method 1 Installation Cost Comparison for Furnaces. This table was creating using data from both the Aspen APEA Economic Analysis Tool and the Equipment Costs Excel Spreadsheet.

Equipment Name	Installed Cost Method 1 [USD]	Installed Cost Method 2 [USD]	Over/Under Evaluation (%)
E2	$9,124,300	$2,615,000	-71.3%
E1XB	$5,638,800	$2,299,000	-59.2%
E7	$99,500	$1,000	-99.0%

Table 16: Installed Cost Comparison for Furnaces. This table was creating using data from both the Aspen APEA Economic Analysis Tool and the Equipment Costs Excel Spreadsheet.

Table 15 demonstrates the total equipment purchase costs and equipment installed costs estimated using Method 1. The difference in these two values equals the cost to install the equipment, or the installation cost of the equipment. As shown in **Table 15,** a large portion of the installed cost is the installation cost. This could indicate that Method 2 does not correctly estimate the installation costs as the Method 1 equipment purchase costs are comparable to the Method 2 installed costs. This is most likely due to Method 2 using outdated methods to calculate installation costs. As shown in **Table 16,** Method 2 highly undervalues the costs by anywhere from 59-71%. While this is not unexpected, this differs from other types of equipment because Method 2 undervalues furnaces that are both small and large in size—therefore it is completely ineffective for costing furnaces. E7 presents the largest difference in the installed cost estimates; the installed cost for E7 for Method 2 is only $1,000. The correlation used for the installed cost estimate in Method 2 is only designed for furnaces that have heat duties in the range of 10-500 million BTU/hr. [5] E7 has a heat duty that does not fall in this range, likely causing the undervaluation by Method 2. Because Method 2 highly undervalues furnaces of all sizes due to outdated installation cost estimates, **the recommendation for sizing furnaces is to use Method 1: Aspen APEA analysis.** This method produces costs that are closer to those expected, is easier to use, and is consistent. Users must take caution when using this method, however, as they must remember to map furnaces appropriately.

Type 7: Distillation Columns

Distillation columns are a type of equipment that is very capital intensive. The styrene process uses two distillation columns—C1 and C2—to achieve the desired molar purity of styrene and to separate the ethylbenzene for recycle. Distillation columns are much more difficult to model than pumps and compressors as utilizing both economic assessment methods requires more user inputs. For both methods, the column is first modeled as a RadFrac distillation column in Aspen. Both of these columns are trayed columns and will be evaluated as such. Method 1 calculates the column as five distinct parts—column, reboiler, condenser, reflux pump, and flash drum. Here, the results from the RadFrac blocks are automatically loaded into the Aspen APEA software for sizing and evaluation. As shown in **Figure 19**, there are only a few user inputs needed to complete the model for the columns (and therefore trays). The bottom material and top material are chosen as carbon steel (CS). The reboilers are calculated as separate pieces of equipment (see **Figure 20**). Calculating the cost of the reboilers using Aspen APEA is relatively simple as all needed quantities are automatically received from the simulation excluding the shell and tube materials materials which the user selects. Reboilers are sized and evaluated in APEA much like the other heat exchange blocks. Therefore, the overall heat transfer coefficients

User tag number	C2-tower	C1-tower
Remarks 1	Equipment mapped	Equipment mapped
Quoted cost per item [USD]		
Currency unit for matl cost		
Number of identical items		
Installation option		
Application		
Base material Bottom	CS	CS
Diameter Bottom section [ft]	21	17.5
Bottom tangent to tangent height [ft]	93	43
Design gauge pressure Bottom [psig]	35.3052	35.3052
Design temperature Bottom [F]	369.248	379.162
Operating temperature Bottom [F]	319.248	329.162
Number of trays Bottom section	43	18
Bottom Tray type	SIEVE	SIEVE
Bottom Tray material	CS	CS
Bottom Tray spacing [ft]	2	2
Bottom Packing material Section1		
Packing height Bottom Section1 [ft]		
Bottom Packing material Section2		
Packing height Bottom Section2 [ft]		
Cladding material Bottom		
Cladding thickness Bottom [ft]		
Thickness Bottom section [ft]		
Corrosion allowance Bottom [ft]		
Base material Middle		
Diameter Middle section [ft]		
Middle tangent to tangent height [ft]		
Design gauge pressure Middle [psig]		
Design temperature Middle [F]		
Operating temperature Middle [F]		
Number of trays Middle section		
Middle Tray type		
Middle Tray material		
Middle Tray spacing [ft]		
Middle Packing material Section1		
Packing height Middle Section1 [ft]		
Middle Packing material Section2		
Packing height Middle Section2 [ft]		
Cladding material Middle		
Cladding thickness Middle [ft]		
Thickness Middle section [ft]		
Corrosion allowance Middle [ft]		
Base material Top	CS	CS
Diameter Top section [ft]	22	23.5
Top tangent to tangent height [ft]	231	31
Design gauge pressure Top [psig]	35.3052	35.3052
Design temperature Top [F]	369.248	379.162
Operating temperature Top [F]	319.248	329.162
Number of trays Top section	113	13
Top Tray type	SIEVE	SIEVE
Top Tray material	CS	CS
Top Tray spacing [ft]	2	2
Top Packing material Section1		
Packing height Top Section1 [ft]		
Top Packing material Section2		
Packing height Top Section2 [ft]		
Cladding material Top		
Cladding thickness Top [ft]		
Thickness Top section [ft]		
Corrosion allowance Top [ft]		
Skirt height [ft]		
Wind or seismic design		
Fluid volume [percent]		
Vacuum design gauge pressure [psig]		
Transition height 1 [ft]		
Transition height 2 [ft]		
Molecular Wt Overhead Prod.	106.139	102.402
ASME design basis		
Allow Resize		

Figure 19. Method 1 Analysis for Trayed Distillation Columns. This figure was reproduced from the APEA evaluation tool on the Aspen Plus simulation created by our team.

User tag number	C2-reb	C1-reb
Remarks 1	Equipment mapped	Equipment mapped
Quoted cost per item [USD]		
Currency unit for matl cost		
Number of identical items	1	1
Installation option		
Heat transfer area [sqft]	30748.2	25533.8
Number of shells		
Heat exchanger design option		
Tube material	CS	CS
Tube design gauge pressure [psig]	170.304	170.304
Tube design temperature [F]	413.61	413.61
Tube operating temperature [F]	363.61	363.61
Tube outside diameter [ft]	0.0833333	0.0833333
Shell material	CS	CS
Shell design gauge pressure [psig]	108.637	108.637
Shell design temperature [F]	369.248	379.162
Shell operating temperature [F]	319.248	329.162
Tube side pipe material		
Shell side pipe material		
Number of tubes per shell		
Tube length extended [ft]	20	20
Tube gauge		
Tube pitch [ft]	0.104167	0.104167
Tube pitch symbol	TRIANGULAR	TRIANGULAR
Shell diameter [ft]		
Tube port diameter [ft]		
Shell wall thickness [ft]		
Shell corrosion allowance [ft]		
Tube sheet material		
Number of tube passes	2	2
Duty [MMBtu/hr]	145.693	98.3223
Vaporization [percent]		
Specific gravity tower bottoms		
Molecular weight Bottoms		
Heat of vaporization [Btu/lbmol]		
TEMA type	BKU	BKU
Allow resize		

Figure 20. Method 1 Analysis for Distillation Column Reboilers. This figure was reproduced from the APEA evaluation tool on the Aspen Plus simulation created by our team.

User tag number	C2-cond	C1-cond
Remarks 1	Equipment mapped	Equipment mapped
Quoted cost per item [USD]		
Currency unit for matl cost		
Number of identical items	1	1
Installation option		
Heat transfer area [sqft]	6078.82	11300.1
Number of shells		
Front end TEMA symbol	B	B
Shell TEMA symbol	E	E
Rear end TEMA symbol	M	M
Heat exchanger design option		
Tube material	CS	CS
Tube design gauge pressure [psig]	18.638	0.304011
Tube design temperature [F]	328.884	285.898
Tube operating temperature [F]	100	100
Tube outside diameter [ft]	0.0833333	0.0833333
Shell material	CS	CS
Shell design gauge pressure [psig]	35.3052	0.304011
Shell design temperature [F]	328.884	285.898
Shell operating temperature [F]	278.884	235.898
Tube side pipe material		
Shell side pipe material		
Number of tubes per shell		
Tube length extended [ft]	20	20
Tube gauge		
Tube length extended [ft]	20	20
Tube gauge		
Tube pitch [ft]	0.104167	0.104167
Shell diameter [ft]		
Shell wall thickness [ft]		
Shell corrosion allowance [ft]		
Expansion joint		
Tube sheet material		
Number of tube passes	1	1
Number of shell passes	1	1
Allow resize		

Figure 21. Method 1 Analysis for Distillation Column Condensers. This figure was reproduced from the APEA evaluation tool on the Aspen Plus simulation created by our team.

User tag number	C2-cond acc	C1-cond acc
Remarks 1	Equipment mapped	Equipment mapped
Quoted cost per item [USD]		
Currency unit for matl cost		
Number of identical items		
Installation option		
Application		
Shell material		
Liquid volume [cuft]	2161.92	1281.78
Vessel diameter [ft]	9.5	8
Vessel tangent to tangent length [ft]	30.5	25.5
Design gauge pressure [psig]	15.0005	15.0005
Vacuum design gauge pressure [psig]		-14.6005
Design temperature [F]	328.616	250
Operating temperature [F]	278.616	127.792
Cladding material		
Diameter of drip leg [ft]		
Length of drip leg [ft]		
Base material thickness [ft]		
Corrosion allowance [ft]		
Cladding thickness [ft]		
Head type		
Allow resize		

Figure 22. Method 1 Analysis for Distillation Column Flash Drums. This figure was reproduced from the APEA evaluation tool on the Aspen Plus simulation created by our team.

for the reboilers can be located in the interactive sizing tool. The condensers are sized and evaluated in APEA much like the reboilers (**see Figure 21**); they are automatically mapped to TEMA shell and tube exchangers by the Aspen APEA software. The material here is also chosen as CS for the shell and tube materials. The overall heat transfer coefficients for the condensors are located in the interactive sizing tool. The column flash drums are named as C2-cond acc and C1-cond acc (see **Figure 22**). Users will only need to update the material specifications if desired. These flash drums—along with the reflux pumps shown in **Figure 9**—are costed as individual equipment, unlike in Method 2. The pumps are mapped to DCP CENTRF. Like the other pumps, user inputs here include only the casing material and driver type.

Method 2 calculates the columns as four distinct parts—column, trays, condenser, and reboiler. A factor of 1.2 is applied to each of these parts to account for other equipment not included in this analysis—such as reflux pumps and flash drums. One simply needs to sum the analysis of these four parts in order to find the total installed cost for the column. As shown in **Figure 23,** after simulating in RadFrac, the user inputs the number of ideal plates, column diameter, and efficiency of the top and bottom sections to calculate the column's installed cost. [6] These parameters are found in the RadFrac results or specified in the Project 1 Assignment Document (as is the case for efficiency.) [3] The design factors are then chosen; these design factors are displayed in **Figure 24.** A design pressure factor of 0.00 is chosen as the pressure is less than 50 psig in the column and the material factor is chosen as 1 for carbon steel. A tray spacing factor of 1.00 is chosen for the 2' tray spacing, the tray type factor is chosen as 0.00 for the sieve trays, and a tray material factor of 0.00 is chosen for the carbon steel trays. Next, the user inputs the condenser and reboiler heat duty, temperature, and utility temperature values which can be found in the RadFrac results. An overall heat transfer coefficient must be chosen based on the nature of the column distillate to be condensed. Since the column distillate consists of light hydrocarbon liquids that are being condensed with a cooling water coolant, a Uo value of 200 BTU/hr-ft^2-°F is chosen. Once this is complete, the user then specifies the design factors for the condensor and reboiler. For the condensor, the material cost factor is chosen as 1.00 for CS shell and tubes, a design factor of 0.8 for a fixed-head exchanger, and a pressure factor of 0.00 since the pressure is less than 150 psig. For the reboiler, all of the same factors are chosen except a design factor of 0.85 is chosen as the reboilers are U-tube reboilers.

Aspen block label	C1	C2
Top sectn. # ideal plates	9	79
Column diameter, ft	23.500	22.000
Bottom sctn. # ideal plates	12	30
Column diameter, ft	17.500	21.000
Over-all efficiency	70%	70%
Top sctn. # actual trays	12.857143	112.85714
Tower height, ft	26.714286	226.71429
Bottom sctn. # actual trays	18	43
Tower height, ft	47	97
Design press. factor	0.00	0.00
Material factor	1.00	1.00
Cost factor Fc	1.00	1.00
Column installed Cost, k$	1691	6039
Tray spacing factor	1.00	1.00
Tray type factor	0.00	0.00
Tray material factor	0.00	0.00
Tray cost factor	1.00	1.00
Tray Cost, k$	183	1042

Condenser		
Heat duty, BTU/h	1.30E+08	1.48E+08
Temperature, F	127.792	278.616
Coolant inlet T, °F	80	80
Coolant outlet T, °F	100	100
Uo, BTU/h-ft2-°F	200	200
DeltaTLM, F	36.89	188.44
Total area required, ft2	17563	3934
Number of shells	4	1
Area per shell, ft2	4391	3934
Material cost factor	1.00	1.00
Design factor	0.80	0.80
Pressure factor	0.00	0.00
Condenser cost factor	0.80	0.80
Condr. Installed Cost, k$	1,757	409
Reboiler		
Heat duty, BTU/h	9.83E+07	1.46E+08
Temperature, °F	329.162	319.248
Steam temperature, °F	363	363
DeltaTR, °F	33.838	43.752
UR, BTU/h-ft2-°F	450	450
Total area required, ft2	6,457	7,400
Number of shells	2	2
Area per shell, ft2	3229	3700
Material cost factor	1.00	1.00
Design factor	0.85	0.85
Pressure factor	0.00	0.00
Reboiler cost factor	0.85	0.85
Reblr. installed cost, k$	731	799

Figure 23. Method 2 Analysis for Trayed Distillation Columns. This figure was reproduced from the Equipment Costs Excel Spreadsheet utilizing values from the Aspen Plus simulation created by our team. [6]

Column Design Pressure

Press, psig	Factor
Vacuum	1.50
0 < 50	0.00
50-100	0.05
100-200	0.15
200-300	0.20
300-400	0.35
400-500	0.45
500-600	0.60
600-700	0.80
700-800	0.90
800-900	1.30
900-1000	1.50

Column Material Factors / Tray Material

Material	Clad	Solid	Factor
Carbon steel	1.00	1.00	0.00
Stainless St.	2.25	3.67	1.70
Monel	3.89	6.34	8.90
Titanium	4.25	7.89	

Design Type Factors

Type	Factor
Floating heac	1.00
U-tube	0.85
Fixed head	0.80
Kettle reboile	1.35

Tray Spacing Factor

Spacing, ft	Factor
2.00	1.00
1.50	1.05
1.00	1.10

Tray Type Factor

Type	Factor
Sieve	0.00
Valve	0.40
Bubble Cap	1.80
Koch Kasca	3.90

Design Pressure Factors

Press, psig	Factor
<150	0.00
150-300	0.10
300-400	0.25
400-800	0.52
800-1000	0.50

Exchanger Cost Factors

Material	Factor
CS/CS	1.00
CS/Brass	1.30
CS/SS	2.81
SS/SS	3.75
CS/Monel	3.10
Monel/Monel	4.25
CS/Titanium	8.95
Ti/Ti	13.05

Estimated Heat Transfer Coefficients for Quick Design, Btu/hr-ft2-F

Condensing Fluid	CW coolant	efrigerant*
Aromatic liquids	200	250
Light hydrocarbon liquids	200	250
Chlorinated hydrocarbons	250	250
Water	250	500

* Assumes nucleate boiling (Delta T between 35 F and 45 F)

Figure 24. User Inputs for Trayed Distillation Columns. This figure was reproduced from the Equipment Costs Excel Spreadsheet. [6]

Comparison of column quantities calculated by the two methods reinforces the accuracy of both methods regarding column/tray design calculations. The number of actual trays calculated by both methods is approximately the same. However, the heat transfer areas in the exchangers do not follow the same trend. The heat transfer area of a heat exchanger—in this case the reboiler or condenser—is indicative of its installation cost. Method 2 greatly underestimates the heat transfer area for the reboilers. However, Method 2 calculates a heat transfer area for the C1 condenser that is greater than the heat transfer area for the C1 condenser calculated by Method 1. This is most likely due to the low operating temperature in this condenser; the correlations in Method 2 may not be equipped to properly estimate costs for condensers with operating temperatures close to utility inlet/outlet temperatures.

Equipment Name	Sub Equipment Name	Installed Cost Method 1 [USD]	Installed Cost Method 2 [USD]	Over/Under Evaluation (%)
C1	Column + Trays	$1,999,300	$1,874,000	-6.3%
	Reboiler	$870,100	$731,000	-16.0%
	Condenser	$340,500	$1,757,000	416.0%
	Flash Drum	$216,900	--	--
	Reflux Pump	$100,800	--	--
	TOTAL	**$3,527,600**	**$4,362,000**	**23.7%**
C2	Column + Trays	$7,009,100	$7,081,000	1.0%
	Reboiler	$1,063,100	$799,000	-24.8%
	Condenser	$250,700	$409,000	63.1%
	Flash Drum	$256,200	--	--
	Reflux Pump	$143,200	--	--
	TOTAL	**$8,722,300**	**$8,289,000**	**-5.0%**

Table 16: Installed Cost Comparison for Trayed Distillation Columns. This table was creating using data from both the Aspen APEA Economic Analysis Tool and the Equipment Costs Excel Spreadsheet.

As shown in **Table 16,** Method 2 undervalues all pieces of equipment except for the condensers and the columns/trays. Both methods are consistent in regards to the combined prices for the columns and trays, with Method 2 being within 1.0-6.3% of Method 1's estimate. However, the condensers are overvalued by Method 2, and the C1 condenser is extremely overvalued—more than 416%. This accounts for roughly half of the cost for this column. This condenser operates at a much lower temperature—127.8 °F—which leads to a greater heat transfer area and therefore increased equipment cost. Method 2 also indicates that the C1 condenser should be comprised of four shells; this also contributes to the high installed cost estimate for the C1 condenser. While Method 2 does provide an accurate estimate for the column and trays, it produces an inconsistent overall estimate due to inconsistency in condenser estimates, underpricing of reboilers, and lack of individual pricing for column flash drums and pumps. Therefore, **the recommendation for sizing distillation columns is to use Method 1: Aspen APEA analysis.** Not only does this method provide a more accurate estimate, it is more consistent and easier to use. No special considerations need to be made for reboilers or condensers that operate at temperatures higher or lower than that which is typical.

Discussion

Both installed cost calculation methods have their pros and cons. As shown in **Table 17,** Method 1 has the greatest total installed cost estimate, 22.1% greater than Method 2. Much of this difference can be contributed to costs associated with units KC1, E2, E7, and E1XB. As evident with small equipment such as KC1 and E7, Method 2 does not scale well. If users design smaller equipment, it will impact their cost assessments greatly. E7, for example, is estimated by Method 2 to cost $1,000 dollars. It is obvious that this is not reasonable, however, this error could be easily overlooked by users. Method 2 is more straightforward and simpler as users are in control of the inputs used for costing and sizing. Therefore, it is easier to understand which factors affect the costing. This method is more tedious, however, as the inputs must be selected manually. Method 1 is more user-friendly and much quicker. Using Method 1 saves a notable amount of time as each time a change is implemented in the Aspen Plus simulation, the Aspen APEA tool automatically updates the economic analysis. When using Method 2, each time a change is implemented, each equipment's data must be located in the Aspen Plus simulation then reinputted into the Excel spreadsheet. This leads to a lot of wasted time that could be saved by utilizing Method 1. This saved time would allow students the opportunity to focus on perfecting other portions of their project. Another benefit of using Method 1 is that a certain level of engineering judgement is

Method	Method 1: Aspen APEA	Method 2: Spreadsheet	Difference	Over/Under Evaluation (%)
Total Installed Cost	$32,086,200	$25,012,000	$7,074,200	-22.1%

Table 17. Overall Installation Cost Comparison. This table was creating using data from both the Aspen APEA Economic Analysis Tool and the Equipment Costs Excel Spreadsheet.

programmed into the software. Users are more apt to choose equipment specifications that are not reasonable such as designing a distillation column that is 23.42377861 feet in diameter or costing a reactor that is 47.8270865 feet tall. Aspen recognizes that these sizes are infeasible and updates them to more reasonable sizes such as 23.5 feet and 48 feet. This tool could lead to a better understanding for users as it enhances their engineering judgement skills. Another benefit of using the Aspen APEA analysis is that there are more individualized material factors. For example, APEA has separate material factors for different variations of stainless steel whereas Method 2 only has one generic material factor for stainless steel. Therefore, **Method 1 should be used in future semesters as it produces a cost estimate closer to what is expected and is more consistent than Method 2.** It is recommended to continue to use Method 2 when sizing and costing flash drums until a more thorough study is completed to achieve a greater understanding of the calculations for either method. This conclusion reflects the underlying hypothesis that Method 1 provides more accurate costing than Method 2. Method 1 offers rigorous sizing ability, individualized material specification factors, and an updated information database providing students with an up-to-date capital cost assessment.

Works Cited

[1] Smith R. Chemical Process Design. Wiley Online Library. https://onlinelibrary.wiley.com/doi/10.1002/0471238961.chemsmit.a01.pub2. Published December 15, 2015. Accessed November 14, 2022.

[2] Towler G, Sinnott R. Chapter 1: Introduction to Design. In: *Chemical Engineering Design: Principles, Practice and Economics of Plant and Process Design*. 3rd ed. Cambridge, MA: Butterworth-Heinemann; 2022:3.

[3] Guillory B. Report 1 Assignment. October 2022.

[4] Al-Malah KIM. Preface. In: *Aspen Plus: Chemical Engineering Applications*. 2nd ed. Hoboken, NJ: John Wiley & Sons, Inc.; 2023:21.

[5] Seider WD, Lewin DR, Seader JD, Widagdo S, Gani R, NG KAM. Chapter 16 Cost Accounting and Capital Cost Estimation. In: *Product and Process Design Principles: Synthesis, Analysis and Evaluation*. 4th ed. Wiley; 2016:426-497.

[6] Corripio A. Equipment Costs.

[7] Chen S-S. Styrene - chen - major reference works - wiley online library. Wiley Online Library. https://onlinelibrary.wiley.com/doi/full/10.1002/0471238961.1920251803080514.a01.pub2 . Published September 15, 2006. Accessed September 28, 2022.

[8] James DH, Castor WM. Styrene. In: *Ullmann's Encyclopedia of Industrial Chemistry*. Weinheim: Wiley-VCH Verlag GmbH & Co. KGaA; 2005:1-17.

[9] Styrene. National Center for Biotechnology Information. PubChem Compound Database. https://pubchem.ncbi.nlm.nih.gov/compound/Styrene. Published September 16, 2004. Accessed September 28, 2022.

[10] AspenTech. Aspen Plus V12 Help. September 2020.

[11] United States consumer price index (CPI)October 2022 data - 1950-2021 historical. United States Consumer Price Index (CPI) - October 2022 Data - 1950-2021 Historical. https://tradingeconomics.com/united-states/consumer-price-index-cpi. Accessed November 8, 2022.