



Federal University of Campina Grande
Science and Technology Center
Chemical Engineering Graduate Program

CostApp: A Cost Estimation Tool developed using C# and WPF for the Chemical Engineering field

Vitor Renan Vitor Gama

Campina Grande – PB

March, 2021

VITOR RENAN VITOR GAMA

**CostApp: A Cost Estimation Tool developed using C# and
WPF for the Chemical Engineering field**

Dissertation presented to the Chemical Engineering Graduate Program from the Science and Technology Center of the Federal University of Campina Grande in partial fulfillment of the requirements for the degree of Master in Chemical Engineering.

Advisor: Dr. Antonio Tavernard Pereira Neto

Campina Grande - Paraíba
March 2021

G184c Gama, Vitor Renan Vitor.
CostApp : a cost estimation tool developed using C# and WPF for the chemical engineering field / Vitor Renan Vitor Gama. - Campina Grande, 2021.
64 f. : il. Color

Dissertação (Mestrado em Engenharia Química) - Universidade Federal de Campina Grande, Centro de Ciências e Tecnologia, 2021.
"Orientação: Prof. Dr. Antonio Tavernard Pereira Neto".
Referências.

1. Estimativa de Custos. 2. Equipamentos da Indústria Química. 3. Desenvolvimento de Software. 4. Equipamentos Industriais. I. Pereira Neto, Antonio Tavernard. II. Título.

CDU 66.0(083.78)(043)

CostApp: A Cost Estimation Tool developed using C# and WPF for the
Chemical Engineering field

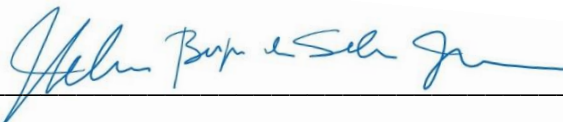
Dissertation approved on: 02/03/2021

Evaluation committee:



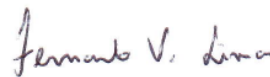
Dr. Antonio Tavernard Pereira Neto (UFCG)

Advisor



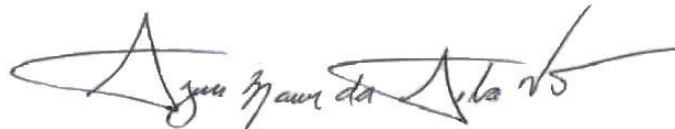
Dr. Heleno Bispo da Silva Júnior (UFCG)

Internal evaluator



Dr. Fernando V. Lima (WVU)

External evaluator



Dr. Sérgio Mauro da Silva Neiro (UFU)

External evaluator

To the amazing humans that
supported me in this long
and hard endeavor.

ACKNOWLEDGEMENTS

First of all, I would like to thank and remind myself of how much work and energy were put into this research. I have doubted myself so many times when I should not have, because I can do it, and this is something that I have to always remember.

To my chosen family, my beloved friends, who supported and encouraged me throughout every step of the way. You guys were my cheerleaders when I did not believe in myself. Thank you!

To my family, my mom, my brother, my aunt and cousins, who helped me get here. You made me feel as if I could accomplish anything that I wanted, and for this I am deeply grateful!

This work, with its highs and lows, was possible thanks to my partner, who checked its grammar, cohesion and coherence flawlessly. His support, his words and kindness gave me strength when I thought I did not have anything else to give.

If there is another professional who deserves my gratitude, that is my therapist. Thank you, Dra. Lucas, for helping me realize all the great things about myself, for helping me to find the confidence and the strength within to deal with the tribulations of being a responsible adult.

I am also grateful to the CNPq, the institution that funded my research and many others in the country. The scientific community in our country is currently facing one of its darkest moments; however, thanks to the CNPq, I was able to get through the first months of the pandemic, and for this I am deeply thankful.

A special thank you to LENP, the laboratory that embraced me and gave me the tools to learn and grow. Thank you to its faculty members and to my colleagues! Their support and fellowship made my days brighter and lighter.

*“Portanto, **angústia** é correlata do **momento** (temporalidade) em que “o **sujeito** está suspenso entre um **tempo em que ele não sabe mais onde está, em direção a um tempo em que ele será alguma coisa na qual jamais se poderá reencontrar”** - Jacques Lacan*

GAMA, V. R. V. **CostApp: A Cost Estimation Tool developed using C# and WPF for the Chemical Engineering field.** 2021. 64 p. Master's degree dissertation in Chemical Engineering. Federal University of Campina Grande. Campina Grande. PB.

ABSTRACT

The accelerated pace in which technology has been developing is affecting different fields of knowledge at different levels. The Data Revolution, also known as the Fourth Industrial Revolution, is creating an environment of deep and fast technological growth, from which the chemical engineering field has greatly benefited, mostly regarding process control and optimization. In order to follow the current digital climate, this research aims to develop a solution that can assist process design engineers and engineering students in the first step to budgeting a new or a section of an industrial chemical process: the cost estimation of equipment. Using cost estimation models found in literature as an estimation engine, the solution was built using C#, XAML and SQLite to create classes that are capable of applying the literature techniques to build a Graphical User Interface (GUI) and, lastly, to enable information storage for the results provided by the tool. The initial performance of CostApp exhibits a coherent behavior concerning the application of the estimation models, and the visual aids and functionalities of the software work as intended. Moreover, the budget provided by the solution is consistent when compared with results taken from other popular solutions from the cost estimating field, such as CAPCOST and the Aspen Capital Cost Estimator. In summary, CostApp is presented a viable option for cost estimation and, as an open-source solution, it can also grow and expand to better adapt to the market or to academic purposes.

Keywords: Cost estimation, Software development, Industrial equipment.

GAMA, V. R. V. **CostApp: Uma ferramenta de estimativa de custo desenvolvida com C# e WPF para o campo da Engenharia Química.** 2021. 64 p. Dissertação de Mestrado em Engenharia Química. Universidade Federal de Campina Grande. Campina Grande. PB.

RESUMO

O ritmo acelerado de desenvolvimento da tecnologia está afetando diferentes áreas do conhecimento em diferentes níveis. A Revolução dos Dados, também conhecida como Quarta Revolução Industrial, está criando um ambiente de profundo e rápido crescimento tecnológico, do qual a engenharia química tem se beneficiado bastante, principalmente no que se refere ao controle e otimização de processos. Visando acompanhar o atual cenário digital, esta pesquisa tem como objetivo desenvolver uma solução que possa auxiliar engenheiros de processos e estudantes de engenharia na primeira etapa do orçamento de um novo ou de uma seção de um processo químico industrial: a estimativa de custo dos equipamentos. Utilizando modelos de estimativa de custos encontrados na literatura como mecanismo de estimativa, a solução foi construída utilizando C#, XAML e SQLite para criar classes que sejam capazes de aplicar as técnicas da literatura para construir uma Interface Gráfica de Usuário (GUI) e, por último, habilitar o armazenamento das informações dos resultados fornecidos pela ferramenta. O desempenho inicial do CostApp exibe um comportamento coerente em relação à aplicação dos modelos de estimativa, e os recursos visuais e as funcionalidades do software funcionam conforme pretendido. Além disso, o orçamento fornecido pela solução é consistente quando comparado com os resultados obtidos de outras soluções populares do campo de estimativa de custos, como CAPCOST e o Aspen Capital Cost Estimator. Em resumo, o CostApp se apresenta como uma opção viável para estimativa de custos e, como uma solução de código aberto, também pode crescer e se expandir para melhor se adaptar ao mercado ou a fins acadêmicos.

Palavras-chave: Estimativa de custos, Desenvolvimento de software, Equipamentos industriais.

LIST OF FIGURES

Figure 1 - Base cost chart for Heat Exchangers	33
Figure 2 - Base cost chart for Centrifugal Pumps	34
Figure 3 - Programming languages ranking of 2020.....	39
Figure 4 - Main window of functionalities.....	50
Figure 5 - Window to edit or add new equipment	51
Figure 6 - Cost estimation windows for Heat Exchangers	52
Figure 7 - Cost estimation window for Pumps	53
Figure 8 - Structure of the Database	55
Figure 9 - Example of data storage	55

LIST OF TABLES

Table 1 - Lang Factors	24
Table 2 - Hand Factors	25
Table 3 - Factor of piping and instrumentation for different process types	27
Table 4 - Installation costs represented as a percentage of the purchase cost.	28
Table 5 - Material conversion	36
Table 6 - Equipment classes developed for the estimation engine	41
Table 7 - Study case data	45
Table 8 - Equipment information from the literature.....	46
Table 9 - Results retrieved from the programmed classes	47
Table 10 - Design information for the Heat exchanger cost estimation	48
Table 11 - Design information for the Towler and Sinnott cost estimation	49
Table 12 - Estimates for the Pumps	56
Table 13 - Estimates for the Heat exchangers.....	57
Table 14 - Estimates for the Reflux Drum.....	57
Table 15 - Estimates for the Distillation Column	58
Table 16 - Final budget for the case study	58

Table of Contents

1. Introduction	13
2. Theoretical background.....	19
2.1. Process planning.....	19
2.1.1. Flowsheet types.....	20
2.2. Cost estimation	21
2.3. Estimation methods.....	23
2.3.1. Lang	23
2.3.2. Six-tenths rule.....	24
2.3.3. Hand.....	25
2.3.4. Order of magnitude estimation model from Seider et al. (2016) ...	25
2.4. Factors that influence the total cost.....	27
2.5. Computer aided chemical engineering	29
2.5.1. Pros and cons of computational chemical engineering	29
2.5.2. Simulation and modelling software	30
2.5.3. Teaching programming in engineering programs.....	31
3. Methodology	33
3.1. Estimation methods.....	33
3.1.1. Guthrie's Method	33
3.1.2. Towler and Sinnott's factorial method	35
3.1.3. Module costing technique by Turton et al.....	36
3.2. Techniques' reliability.....	38
3.3. Software development	38
3.3.1. Estimation engine	40
3.3.2. User Interface	41
3.3.2.1. MainWind.....	42

3.3.2.2. EquipSelect.....	42
3.3.2.3. Equipment screens	43
3.3.3. Database connection	43
3.4. Case study for validation of the software.....	44
4. Results.....	46
4.1. Analysis of the estimating modules programmed	46
4.1.1. Cost curve	46
4.1.2. Guthrie.....	48
4.1.3. Turton et al.	48
4.2. User interfaces	50
4.2.1. Main window	50
4.2.2. Equipment and Model selection	51
4.2.3. Equipment screens	52
4.2.4. Information storage.....	54
4.3. Case study discussion	56
5. Conclusions	60
REFERENCES	62

1. Introduction

Engineers rely on concepts from different areas of science, philosophy and mathematics to generate, from their own ideas, new techniques and tools capable of manipulating the environment and raw materials to achieve specific objectives in a safe, concrete and economically viable way.

Developing an entirely new process requires time and experience, as Sean Moran (2015) quotes: "Process plant design is an art." Though engineers resort to a number of different techniques, for instance, process simulations, technical drawings, spreadsheets macros, etc., their professional judgment and creativity cannot be replaced by any other tool.

Still according to Moran (2015), when solving a problem, engineers have an extensive spectrum of different tools that help in deciding which possible solution can be applied. This also distinguishes professionals with and without experience in the area, since the most experienced are more likely to have dealt with similar situations to the problem presented, and this empirical knowledge allows them to make more assertive decisions in the search for adequate results.

The initial design phases in chemical engineering are essential to acquiring information on the capacity and cost of the process. These data will indicate which estimates can be studied within the limits of a given process and the approximation of the necessary investment is formalized. Only after these steps can the possible yield of the plant be evaluated, and the project rejected or accepted since the objective, in most cases, is profit (TOWLER et al., 2013).

The ability to estimate costs in a more concrete and assertive manner has acquired a new status after the economic crisis faced in 2008. With financial institutions imposing greater restrictions on financing after the crisis, the need for more accurate estimates was highlighted, assuming a very important role in the development of a project. Previously, it was commonplace for projects around the world to exceed construction time and budgets, with cases such as the channel between the UK and France, which exceeded the budget by 80% and funding by 140% (SMITH, 2014).

Also according to Smith (2014), several international organizations felt the need for better methods of control, estimation and planning. To meet this requirement, the formalization and standardization of the people working in this

area must take place, as well as a more specialized training of professionals to ensure that efforts to contain losses are available - commonly found in several enterprises in several continents - and adequate remuneration for the class.

Cost engineering or economic engineering are the designations most commonly used to classify the area in which chemical engineers, process engineers and administrators work in order to better conduct projects. Roy (2008) states that cost engineering includes cost and investment risk estimation, profitability analysis, cost control, business planning and management, as well as project planning, management and scheduling. It also explains deeply the concept of estimating costs, conceptualizing it as a prediction of the possible price that a product or service will acquire based on information of the present moment.

A definition of price in the scope of project design is given by Ulrich (1984), in which the author focuses on the fixed cost. This value represents the amount that must be invested in equipment and devices for industrial plants and that is why it is named as "fixed", because it cannot be easily transformed into another form of capital. One of the reasons for this restriction is that, in the case of industrial equipment, its construction is often specific to a process and must meet the unique conditions of a projected plant, the opposite of a common appliance that will work for many conditions soon after being purchased.

Some companies located in different continents specialize in the acquisition, design and construction of industrial processes. The decision process on which company should conduct the project takes place through the evaluation of each proposal, in which the estimate of the total cost is a decisive factor in the final choice. Therefore, companies in this field that do not have a good database and experienced professionals in design and engineering face greater obstacles in the formulation of established cost approximation (PUTRA and TRYIONGO, 2015).

Estimating costs is decisive for any project and Moran (2015) debates different techniques in producing these estimates. The academic approach, according to the author, is produced by students and provides values that "marvel because of their size"; however, they are still underestimated. Another approach discussed has the main advantage of taking a few seconds to be developed, called "Economic potential", which evaluates only the values of products and raw

materials. In the event that a product has a higher value when compared to its raw material, it is said that the process is economically profitable.

Both approaches have disadvantages: the academic one with a complex and imprecise formulation, and the other one works with gigantic imprecision bands; however, the author also approaches professional techniques with greater accuracy. These methods are based on quotations acquired directly from vendors and companies specialized in the construction of equipment, on the engineering work involving electrical installations, piping and also based on computational tools.

Cost estimation is a field explored not only by engineers. Computer scientists, software developers, programmers, and other professionals in this area have also studied and created their own methods and procedures to assess cost and labor involved in new projects. There are similarities between the steps taken by engineers and by software developers, one of which being the fact that both organize processes by firstly estimating the size of the projects so that the labor, schedule and the final cost can be estimated (SHEKAR AND KUMAR, 2016).

Boehm, Abts and Chulani (2000) conducted a survey to summarize the models and techniques used to estimate the cost of software development projects. The authors present some of the uses of this cost approximation, such as budgeting, risk analysis, trade-off, project planning and control, functioning similarly to the cost estimates developed in engineering and design projects.

In the earlier moments of the design of any chemical process, there is a wide range of different approaches toward the end product. These alternatives are evaluated and weighted against some basic goals, such as overall cost, efficiency, environmental impact, endurance of the final product, etc. The decision process relies on this evaluation to select among the various routes, for instance, which of them agrees with the standards set to the process and also whether or not its design proves to be cost-effective (WECHSUNG et al., 2010; MAO, Z., YANG, C., 2016).

Due to its complexity, chemical processes require a well-established knowledge about reaction kinetics, as well as a set of precise thermodynamic data (WECHSUNG et al., 2010). However, in the work of Ibrahim (2011), he discusses the cost associated with building and maintaining engineering

laboratories, raising the question of how one can work to design an entire process lacking vital information.

The tools to tackle the problem stated above have been populating the industry and the academy. According to Mao and Yang (2016), computational technologies are elevating the understanding of chemical processes to a higher standard, exposing that many new journals focused on computational or numerical solutions have appeared in the past two decades, as well as a great number of books and monographs that have been developed toward the computer-aided simulation field.

Ibrahim (2011) also explores commercial simulation programs. These software packages are divided into two classes: general and dedicated simulation packages. The general package works in a wider range than the dedicated one, working for various engineering problems and for different branches of engineering. Examples of these programs are Matlab and Excel. The dedicated simulation package class, on the other hand, functions to simulate specific conditions in a determined field. As examples of dedicated simulation software to simulate chemical processes, there is CHEMCAD, and also the Aspen Plus package.

Bojorge et al. (2014) brought forward the advantages and importance of using computational tools in the field of chemical and petroleum engineering. Working with these programs allows engineers to develop different dispositions of a possible process, analyze its dynamic or stationary behavior according to different adjustments, send signals to process plants and evaluate the response of their control systems, making it possible to simulate real work conditions and, consequently, resulting in a better understanding of how the process functions.

The advancement of technology partnered with the chemical industry not only enabled a deep understanding of the production process, but also strongly contributed to the safety of industrial plants. Patle et al. (2014) elaborated that chemical processes need skilled operators since many of these processes are deeply complex and present dangerous working conditions, such as highly pressured vessels, toxic gases, high temperatures pipes, among others.

Due to this severe environment, chemical plants became highly automated to ensure that workers could operate them without endangering their lives.

Nevertheless, in order for these operators to acquire the knowledge to handle different situations that might emerge, the development of Operator Training Systems (OTS) is of most importance, after all, industrial plants are increasing their automation and by doing so, as stated above, there is a need for a well-trained workforce. Despite such need, according to Moran (2015):

“Universities still teach students approaches to unit operation sizing based on hand calculations using charts which come from the slide-rule era. Many who do this think it helps students to understand the unit operation—whether this is true or not, it isn’t much to do with modern professional practice, since process plant designers mostly use spreadsheet programs to do their calculations.”

In the present global context, there are profound changes taking place, and technology has been the driving force in many aspects of the industrial and social aspects of the human experience. After the worldwide economic crisis of 2008, the attention paid to budgeting and planning was accentuated, and along with it, the requirement for specialized cost management professionals has been highlighted (SMITH, 2014).

Chemical engineers are in the front line of production. Not only do they face the current status of the society and its demands - to deliver quality products while optimizing both the disposal of waste and the expenditure of energy - but such professionals also have to discuss the next steps in the development of their own field (MAO, Z., YANG, C., 2016). On this note, Bojorge et al. (2014) and Santos et al. (2018) highlight the accomplishments that can be achieved by chemical engineers that explore computational and programming skills to innovate and follow the advancements brought by Industry 4.0.

Tackling the aforementioned issue, this work aims to gather the knowledge of chemical engineering and computer science to develop solutions for chemical engineering students with a well-grounded understanding of programming. The main objectives to be reached by this research are:

- To create a simple platform to estimate the cost of industrial equipment;
- To highlight the importance of programming in the chemical engineering field;

- To compare the calculated estimates with values acquired by other popular software from the field;
- To build the foundation to deeper and wider research in chemical processes and chemical engineering solutions allied with new technologies to better adapt to the technological growth of our current society.

2. Theoretical background

2.1. Process planning

The starting point of any industrial process depends on the necessity for a product that will supply a third party or function as input for the next stages inside a production chain. However, in order to meet the market demands for any particular commodity, the industrial process that will provide such resources must be thoroughly designed.

Towler et al. (2013) divide the industrial process construction into two phases: process design and plant design, each phase relying on different professionals to cover specific steps in the development of a plant. Initially, in the conceptualization of the process, the efforts are focused on which process arrangement will be the most suitable to produce a specific product or products.

Moran (2015) also discusses process planning, arguing that, at this concept step, most companies seek specialized workforce to carry out the design of the process, it being, for the most part, an engineering consultancy company. The work to be done at this point revolves around the determination of operation constraints, the specification and selection of equipment, and the development of flowsheets with the most probable arrangements to be built.

Once design engineers are satisfied with one of the many possible structures for the process, they will discard the other options and, according to Moran (2015), 98% of all discussed options do not reach the construction stage. At this moment, the efforts gravitate toward the plant design, described by Towler et al. (2013) as a phase in which the work is carried out by a number of different specialties to cover different projects in the plant design, such as mechanical equipment design, civil construction, electric wiring, etc.

Coker (2007) affirms that well-established knowledge of the intersections of the engineering fields is essential to a thorough design. The start of a project must be based on an idea that is clear and concise so that the planning created can be carried out well. The details of the project can be classified into:

1. Preliminary design
2. Detailed-estimated design
3. Detailed design

The preliminary design functions as a checklist for anything that can be adjusted in the process. A shorter evaluation time is given at this stage, and depending on the results obtained, a detailed design will be developed. Even if the equipment lacks specific information in the Detailed-estimate design, it will execute more accurate calculations and analysis. If the evaluation of the previous step indicates that the process will be profitable, a precise detailed estimate is developed. The final detailed design will comprise complete specifications for the components and equipment, blueprints of the plant, and the costs based on quoted prices. From this point on, the plant construction is all set to start (PETERS and TIMMERHAUS, 1991).

2.1.1. Flowsheet types

An important piece of the design is the plant flowsheet. Coker (2007) defines the elements that compose a concise flowsheet, which are: identification of the chemical process steps in an organized sequence, and detailed information to make it possible to interpret the chemical requirements mechanically.

Process diagrams vary according to the amount and type of information that is intended to be displayed. The Block Flow Diagram (BFD) is usually the first type of diagram to be presented to chemical engineering majors. It is mostly applied to enlighten how mass and energy balances are calculated, consisting only of blocks connected by lines with information concerning flowrate, pressure, temperature and even some of the components' composition, not including the type of equipment or operation involved (TURTON, 2012).

Process Flow Diagrams (PFD) are the visualization of the mass and energy balances. In commercial PFD, the information included ranges from the definition of all major equipment used to utility streams and basic control loops. The level of complexity of a PFD is much greater when compared with a BFD since it comprises specific data of each operation used in the plant (MORAN, 2015; TURTON, 2012).

Piping and Instrumentation Diagrams (P&ID) involve connections between pipelines, vessels, tanks, columns, etc. They also include information regarding size, schedule (thickness) and type of material used in the construction of the

pipes and the equipment. P&IDs are a representation of the mechanical and electrical structures of the plant without some of the information of the chemical process, since they are diagrams used by engineers who do not necessarily have knowledge about the chemical process (COKER, 2007).

2.2. Cost estimation

Predicting the expenses involved in the development of a product or service is imperative. Cost estimation is the methodology applied to foresee the expenditures associated with the production process. The application of this technique in earlier stages of the designing work can lead to meaningful budget savings (ROY, 2008).

The cornerstone of the cost engineering field is the estimates. They are applied in the design process in order to analyze its feasibility and also compare it with alternative process designs. The accuracy of an estimate depends on how much work is invested in its development; however, the value calculated will always be an approximation, not an exact number (HUMPHREYS, 2005).

The development of precise documentation of the chemical process features, such as PFDs and P&IDs, is essential since it will be a source of information regarding the evolution of the project. The access to this data will inform engineers how much of the process is known and from it, they will be able to adjust the time and effort directed to formulate the estimate and its class (COKER, 2007).

Moran (2015) explains in his work that when designing a process, an economic evaluation must be quickly developed to guide engineers toward the most feasible option. Therefore, the factorial method is applied to the major operations of a factory in order to approximate their costs, providing information that could give engineers a better understanding of the profitability of the process. Nevertheless, he points out that the application of this method happens more frequently inside academic environments than in real chemical plants.

Amsterdam (2018) conducted a study on factorial methods and their influence in the cost engineering field. These methods started being developed after the Second World War, following the economic growth of the United States of America, and in order to apply them, the process flowsheet must provide

information on the equipment that will be purchased. With this information, the equipment is priced and specialized factors are applied to include a number of associated costs, such as construction, freight, taxes, etc.

To correctly apply industrial cost estimation methods, AACE International (2016) brings together a set of guidelines that provide a broadly accepted generic classification system of industrial processes. Among the guidelines proposed in Recommended Practice 18R-97 are estimation classes. Described below, they encompass engineering, procurement, and construction practices.

- Class 5 or Order of magnitude

Estimates of this class are based on limited information, little more than plant type and location is known during this estimate. At this stage, there is a short project delivery range, between 0-2% of the total. Usually, only block diagrams have been approved and due to this information limitation, their accuracy range is from -50% to -20% at the lower limit, and from 30% to 100% at the upper limit.

- Class 4 or Study Estimate

This class is applied shortly after the previous one and, since it contains more information, it is used to design the project suitability analysis, determine feasibility, etc. The project delivery ranges from 1% to 15% and, by this time, the project should already have plant capacity data, layout and process flow diagrams. Its accuracy ranges from -30% to -15% at the lower limit, and from 20% to 50% at the upper limit.

- Class 3 or Preliminary design estimate

To be classified in this class, an estimate must have been designed to allow approval of the budget or process funding. The project, at this point, is between 10% and 40% complete and features process flow diagrams, essential service flow charts, preliminary piping diagrams, among others. The accuracy range for this class goes from -20% to -10% at the lower limit, and from 10% to 30% at the upper limit.

- Class 2 or Engineering estimate

Estimates of this class function as parameters through which the contracting party can monitor project costs and progress. The estimate belonging to this class is used as an offer to the hiring company and from it, the contract value is established. The project progress is between 30% and 70% complete and includes various pieces of information, such as material and energy balances, process flow diagram, final layout drawings, single line diagrams, electric motors, piping and instrumentation diagrams, etc. Accuracy ranges from -15% to -5% at the lower limit, and from 5% to 20% at the upper limit.

- Class 1 or Final estimate

The development of a class 1 estimate is mainly focused on analyzing individual plant sections, which are the most important or critical in the process design. Due to its use in very important sections, this type of estimate is as thorough as possible, requiring the most accurate methods. The sectors analyzed with the aid of this estimate are generally the ones that subcontractors will bid or in which the responsible engineers will make verification estimates. Overall, the project is now between 65% and 100% complete, with complete project documentation, design, execution plans, and project commissioning. Typically, the accuracy for this estimate ranges from -3% to -1% at the lower limit, and from 3% to 15% at the upper limit.

2.3. Estimation methods

2.3.1. Lang

The history of the cost estimating field started around 1947/1948 when Lang published the first factorial method. Until that point, only major equipment had been taken into account; however, with his method, Lang took a turn and

included the items that had not been considered as a factor, F_L , of the total amount, C_K , estimated for the other pieces of equipment.

$$C_L = F_L * \sum_{n=1}^k C_K \quad (1)$$

Equation (1) represents the estimating model developed by Lang, and the factor F_L varies according to three different situations presented in Table (1) below. Even being the most cited technique, the reliability of Lang's factors is questioned since he does not present any statistical data to support his factors. Moreover, only 6 out of 14 chemical plants in his study were real built plants (AMSTERDAM, 2018).

Table 1 - Lang Factors

Type of process	F_L
Solids	3.10
Solids/Fluids	3.63
Fluids	4.74

Source: Towler et al. (2013)

2.3.2. Six-tenths rule

The six-tenths rule is another method widely used in the cost engineering field. Shabani and Yekta (2015) present in their work the characteristics of this technique, being the most attractive one its simplicity. In this approach, the necessary information includes only the capacity and cost of a specific piece of equipment, or even the capacity and cost of the entire plant, in order to estimate the price of purchase of a similar piece of equipment or plant with a different capacity.

Considering the required data as L_1 and C_1 through the application of equation (2), it is possible to determine the approximate cost, C_2 , of similar equipment of capacity L_2 .

$$\frac{C_2}{C_1} = \left(\frac{L_2}{L_1}\right)^m \quad (2)$$

The exponent, m , is the cost exponent or capacity factor. It typically lies between 0.5 and 0.85, varying by equipment and plant type. However, in the chemical industry, a value of 0.6 is commonly used, thus naming the model (LEMMENS, 2016).

2.3.3. Hand

Hand's (1958) approach is similar to that of Lang since it also weighs the estimated cost of the equipment with factors that would improve its accuracy. Nevertheless, the factors provided by Hand are specific to the type of equipment rather than the type of process. This model is also limited to providing the estimated cost considering the battery limits of the plant.

$$C_H = \sum_{n=1}^k F_H * C_K \quad (3)$$

Table 2 - Hand Factors

Equipment type	F_H
Compressors	2.5
Columns	4.0
Furnances	2.0
Heat Exchangers	3.5
Instruments	4.0
Miscelaneous	2.5
Pressure Vessels	4.0
Pumps	4.0

Source: Towler et al. (2013)

2.3.4. Order of magnitude estimation model from Seider et al. (2016)

Based on Hill's (1956), this model can provide a source of information on the probable cost of the plant in an initial designing step, especially at the moment when different process configurations are still being discussed. This estimation model has proved to be reliable in petrochemical processes, in which it presented

a $\pm 50\%$ accuracy. In order to apply this technique, it is necessary that the major equipment and the plant flowsheet be thoroughly planned.

It is also necessary to follow a set of restrictions, such as using the Marshall and Swift Process Industries Average Cost Index from 2006 with its value of 1365, applying a production basis of 10.000.000 lb./year for the main product and, finally, the material of construction and pressure of the most important pieces of equipment (not including heat exchangers and liquid pumps) are, respectively, carbon steel and less than 100 psi.

To achieve the total bare-module cost, it is necessary to go through three steps:

- First step:

Apply the six-tenths rule to the weighted current production of the main product by the basis of the model, achieving a production rate factor (F_{PR}):

$$F_{PR} = \left(\frac{\text{Flow rate of the main product, lb/yr}}{10000000} \right)^{0,6} \quad (4)$$

- Second step:

Calculate the individual cost module, C_M , of the most important pieces of equipment, excluding heat exchangers, flash, reflux drums and liquid pumps. The design pressure of each piece of equipment is required in this step; however, if it exceeds 100 psi, the pressure should be converted to psia and later applied to Equation (5) below:

$$C_M = F_{PR} F_M \left(\frac{\text{Designed pressure}}{100} \right)^{0,25} * (\$ 160.000,00) \quad (5)$$

F_M is the material of construction factor. Its value is 1 to carbon steel, which is the model's default material, and the values for other materials are presented in Seider et al. (2016).

- Third step:

Lastly, the total cost of the module is the sum of the individual cost module of each piece of equipment multiplied by F_{PI} , a factor that encompasses the cost of piping, instrumentation and controls, and other indirect costs presented in Table (3). This factor, similarly to Lang's model, considers the type of process in order to be applied.

$$C_M = F_{PI} * \left(\frac{MS \text{ index}}{1365} \right) * \sum C_M \quad (6)$$

Table 3 - Factor of piping and instrumentation for different process types

Type of process	F_{PI}
Solids	1.85
Solids/Fluids	2.00
Fluids	2.15

Source: Seider et. al (2016)

2.4. Factors that influence the total cost

There is some additional information, besides the approximated cost of the equipment, which should be considered by the cost engineer when performing the economic analysis of any project. The price of the purchased equipment, for instance, is - in most cases - free onboard (F.O.B), which means that the cost of its shipment should also be paid by the company that bought it (ULRICH, 1984).

Some attention should also be addressed toward the construction materials used in the equipment since they could significantly affect its cost. The material factor, f_m , is reported in the literature as an average value that could be applied to evaluate the cost of a specific piece of equipment, but from a different construction material (SMITH, 2005). In order to calculate the material factor, one should divide the purchase cost of the equipment built with a specific material by the purchase cost of the same equipment built with carbon steel (TOWLER et al., 2013).

Regarding the costs involved in the installation of the acquired machinery, its value ranges differently for each piece of purchased equipment. To accurately weigh how much of its purchase cost will go toward its installation, it is necessary to evaluate the specific characteristics of the equipment, the location where it will be installed, the materials and labor involved in loading and unloading it, in building foundations and supports, and also in the expenses on electric and piping connections (GARRET, 1989; ULRICH, 1984).

To consider the associated costs involved in the installation of the purchased equipment, Peters and Timmerhaus (1991) presented in their work the installation costs as a percentage of its purchase price, as shown below in Table (4).

Table 4 – Installation costs represented as a percentage of the purchase cost.

Equipment	%
Compressor	30-60
Centrifugal separator	20-60
Dryer	25-60
Evaporators	25-90
Filters	65-80
Heat exchangers Mechanical crystallizers Metal tanks	30-60
Mixers	20-40
Pumps	25-60
Towers	60-90
Vacuum crystallizers	40-70
Wood tanks	30-60

Source: Adapted from Peters and Timmerhaus (1991)

Several authors from the cost engineering field have published and discussed the effects of time on the estimates. Both Humphreys (2004) and Turton et al. (2012) presented in their works a common strategy to damp the effects of inflation on the estimated cost. Moreover, according to Smith (2005), published cost data are, in most cases, outdated and from many different sources, and to include these disturbances, cost indexes should be applied.

The methodology to apply cost indexes is very straightforward, as shown by Kenneth (2004). To achieve the updated cost for a specific year, C_2 , one should consider the cost index that corresponds to the same year as that of the information used in the estimate, I_1 , as well as the one that corresponds to the desired year.

$$\frac{C_2}{C_1} = \frac{I_2}{I_1} \quad (7)$$

First of all, one should select from a variety of cost indexes reported in the literature, such as The Chemical Engineering Plant Cost Index (CEPCI) and The Marshall & Swift (MS) Equipment Cost Index, both published monthly in the Chemical Engineering magazine; and The Nelson-Farrar (NF) Refinery Construction Cost Index, published in the Oil & Gas Journal in order to update and also set a common basis for all the estimates (SEIDER et. al, 2016; SMITH, 2005; SYMISTER, 2016).

2.5. Computer aided chemical engineering

2.5.1. Pros and cons of computational chemical engineering

The chemical engineering field deeply explores two subjects that are considered its cornerstones, namely unit operations and transport phenomena. In addition to these two paradigms, Mao and Yang (2016) discussed in their work the influence and the role that computational chemical engineering performs when associated with the other aforementioned paradigms. According to the authors, computational chemical engineering supplies the tools to deepen the knowledge of the field and, by doing so, it reaches levels of understanding never attained before. They also believe that this computational aid will lead to advancements on sustainability and green production, as well as in catalyst design, process optimization, numerical experiments, scaling up plants and equipment, etc.

Despite all of its applications and possibilities, Moran (2015) warns us, in his work, about the misuse of these technologies. For the author, computational tools have been overused in academic environments in order to compensate for a gap of knowledge regarding process design, creating a scenario in which such

programs could replace professional judgment when their actual role is – only – to support it.

Moran (2015) also discusses how to approach the application of software to the chemical engineering practice. The author states that by following the Institution of Chemical Engineer's (IChemE's) Computer-Aided Process Engineering (CAPE) guidelines, engineers can make effective use of these programs if they have also validated the models inserted in the software.

2.5.2. Simulation and modelling software

Performing numerical simulation, process optimization and fluid dynamics analysis a few decades ago was very time consuming; however, with the introduction of computational tools to the chemical and oil industries in the 1960s, these tasks became much more accessible and user friendly due to graphical interfaces programmed with object-oriented methods (PATLE et al., 2014; MAO and YANG, 2016).

Process simulators are part of the chemical engineering field because they allow the development of different scenarios for the intended processes, as well as test them without actually building an industrial plant only to study the hypotheses discussed. Alvarado (2012) states that simulation software is a powerful tool, capable of predicting the conditions of processes, adjusting operation conditions, estimating the cost of the equipment and also optimizing process variables.

Moran (2015) cites, in his work, some of the most popular types of simulation software. The first simulator discussed is AspenTech's HYSYS, which the author explains that, due to its configuration, could be used by the petrochemical and oil industry for process optimization.

The following simulator discussed is Pro/II, which performs steady state analysis and is also very popular in the oil and gas industries, even more popular than HYSYS. AspenTech have a variety of products in addition to the aforementioned software. To perform steady state simulations, the company has the Aspen Plus software available. It can be used in the conceptualization or optimization of different processes since it comprises an extensive database on chemical and physical properties of hundreds of components (SOUZA, 2011).

In addition, according to Bojorge et al. (2014), the association of computational tools with the learning process in engineering environments is essential because it helps to create a more solid foundation for theoretical concepts, giving students a competitive advantage.

2.5.3. Teaching programming in engineering programs

Chemical processes are, in most cases, highly complex and, due to their complexity, any alteration in one particular operation can cause an impact wave throughout the entire process plant (Wechsung et al., 2010). In his work, Souza (2011) argues that the commercial software available in the market does not allow users to introduce their own models and data.

Nonetheless, some professionals are working to fill this gap by writing their own code, using several different tools and programming languages to create more flexible software in order to achieve specific solutions to specific problems not considered by common commercial process simulators.

In order to be able to improve the models in commercial simulators and develop new solutions, engineers should learn how to code. This task demands a certain set of skills, such as high-level logical reasoning, problem-solving, computational thinking, among others. These skills, however, need to be learned and practiced since they do not come naturally for everyone (SANTOS et al., 2018; TOPALLI, D., CAGILTAY, N. E. 2018).

Bojorge et al. (2014) also argues that computing knowledge is essential to engineering students since operating and designing a process has become much more computational in the past decades. The technology has allowed virtual laboratories to be developed, which means that the expenses on raw materials and reactants can be minimized since experiments and training can be done remotely and safely (BOJORGE et al., 2014; IBRAHIM, D., 2011).

Clough (2002) discusses how, what and who should teach introductory programming in chemical engineering majors. He mentions his case, using as an example the chemical engineering major at the University of Colorado, which changed their programming teaching structure and yet preserved some key aspects, such as engineering problem-solving and structured programming.

This change led to some meaningful benefits for their students since, according to Santos et al. (2018), learning how to code at undergraduate level can help students to handle technical issues and also stimulate skills for which employers look in young professionals. In the digital era in which we current live, combining technical engineering knowledge with advanced programming abilities can create job opportunities never before explored.

3. Methodology

This section will present the steps taken toward the development of a cost estimation software that can be applied to a number of different pieces equipment from the chemical industry in order to determine their updated estimated cost. Grounded on the knowledge built from the previous section, it will present the techniques and technologies applied in this work, as well as a proposed study case that can corroborate this research.

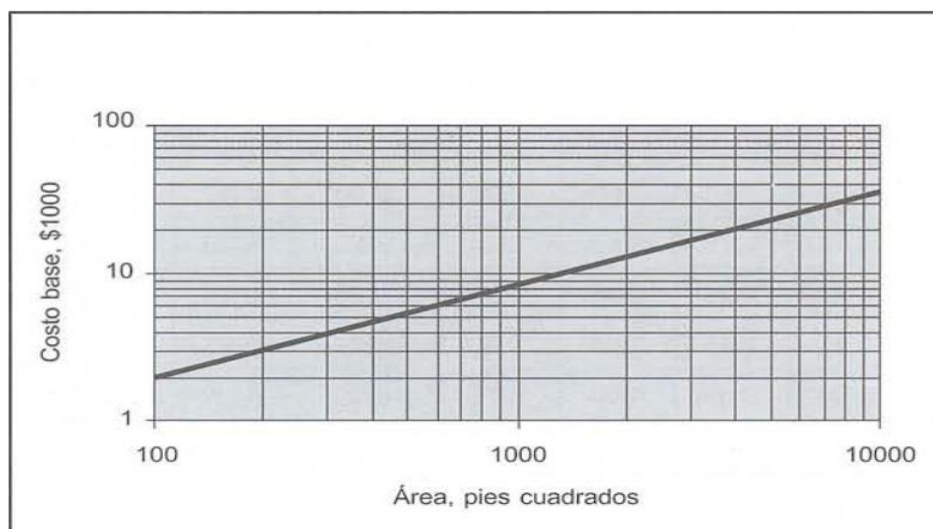
3.1. Estimation methods

In order to acquire the estimated fixed cost of industrial plants, all of the major pieces of equipment involved in the process must have their purchase values estimated. The estimation process will be covered in this work by three methods that are based on the Module Costing Technique, namely Guthrie's (1969), Sinnott and Towler's (2013) and the one by Turton et al. (2012).

3.1.1. Guthrie's Method

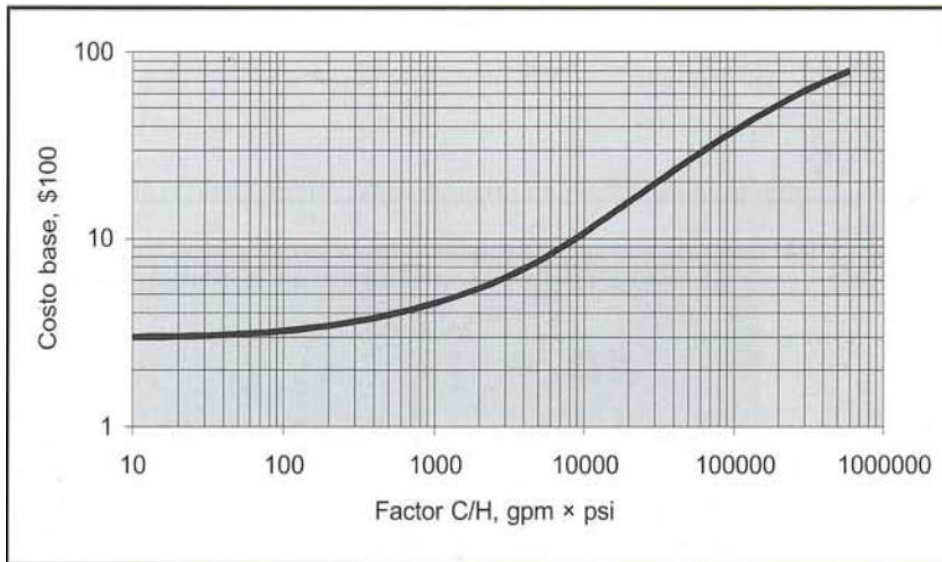
Gutiérrez (2003) shows how to apply Guthrie's methodology toward the total cost of the module. The first step requires that the engineer consult the respective chart of the desired equipment to acquire the information of its base cost depending on its capacity. Unfortunately, this technique is limited by the small variety of equipment charts.

Figure 1 - Base cost chart for Heat Exchangers



Source: Gutiérrez (2003)

Figure 2 - Base cost chart for Centrifugal Pumps



Source: Gutiérrez (2003)

In order to automate the process of acquiring the base cost for the equipment encompassed by Guthrie's technique, equations that represent the equipment's base cost behavior, shown in Figure (1) and (2), were withdrawn from EPE (2018). The next step toward the estimate is the adjustment of the base cost through factors that can comprise different types of geometry, F_D , material of construction, F_M , and, finally, for the process pressure, F_P , of a specific piece of equipment. These factors are presented by Gutiérrez (2003) and applied according to specific relationships for each piece of equipment. Equation (8) below exemplifies the relationship between the variables in order to estimate the free-on-board cost of a heat exchanger:

$$C_{FOB} = \text{base cost} * ([F_D + F_P] * F_M) \quad (8)$$

In the previous step, the base and free-on-board costs were determined from cost charts and through the application of specific factors to the base cost, respectively. Now, in order to calculate the bare module (C_{BM}), one should apply the respective bare module factor, F_{Mod} , to the base cost and, finally, calculate the bare module adjusted cost (C_{BMA}), through the following equations:

$$C_{BM} = \text{base cost} * F_{Mod} \quad (9)$$

$$C_{BMA} = C_{BM} + (C_{FOB} - C_B) \quad (10)$$

The bare module adjusted cost corresponds to the value of the desired equipment in 1968; therefore, it is necessary to update this value using Eq. (7) and applying cost indices (CEPCI, MS, NF) from the desired year.

The final step of this method applies a 15% factor to the updated value, aiming to take into account the influence of contingencies that may appear.

3.1.2. Towler and Sinnott's factorial method

According to the research conducted by Amsterdam (2018), this technique falls into the Modern Database method group, which means that it is characterized by the way it exhibits its cost databases and not how it applies the factorial method. The technique's characteristic equation is a type of six-tenths rule with exponential behavior.

$$C_e = a + b * S^n \quad (11)$$

The parameters a , b and n are constants that correspond to a unique piece of equipment. S is the size/capacity variable and, depending on the type of equipment, it could be the flowrate, volume, heat transfer area, mass, etc. The estimated costs achieved by this model, C_e , are in the U.S. Gulf Coast basis from January 2010.

In order to achieve the Inside Battery Limits (ISBL) cost, one should apply some correction factors to the estimated cost. First of all, the factorial method presented by Towler and Sinnott considers most of its equipment to be constructed from carbon steel, a common metal alloy; therefore, a material factor should be applied to all equipment built with different materials. Table (5) below exhibits some average values used as conversion factors, f_M , to consider the construction of the equipment from a material other than carbon steel.

$$C_{fm} = C_e * f_M \quad (12)$$

Table 5 – Material conversion

Material	f_M
Aluminum and Bronze	1.07
Cast steel	1.1
304 and 316 stainless steel	1.3
321 stainless steel	1.5
Carbon steel	1.0

Source: Adapted from Towler et al. (2013)

With the information on all major pieces of equipment and their costs properly estimated and adjusted to the material of construction needed, HAND factors can be applied. By employing these factors, shown in Table (2), the influence of costs on construction, installation, transport, taxes and fees, etc. are encompassed in the estimated cost of each piece of equipment.

$$C_H = f_H * C_{fm} \quad (13)$$

The ISBL cost for the whole plant is given by:

$$C_{ISBL} = \sum_i^n C_{H,i} \quad (14)$$

It is important to remember that all the parameters used in the model have their basis in January 2010; consequently, the effects of time must be taken into account by using Eq. (7) and the corresponding cost indices for the base and desired year.

$$C_{ISBL(X)} = C_{ISBL(2010)} * \frac{I_{(2010)}}{I_{(X)}} \quad (15)$$

3.1.3. Module costing technique by Turton et al.

Turton and his collaborators have worked on a more detailed method, trying to be thorough in their analysis of the costs involved in the construction of an industrial process. This technique is often used when developing a brand-new process due to its rigorous calculation.

The starting point of this method is acquiring the equipment purchase cost at base conditions (operating pressure near atmospheric and carbon steel as

construction material), as well as the bare module factor and others factors that can encompass the effects caused by higher operating pressures and exotic materials of construction.

The bare module cost is determined by Eq (16) below:

$$C_{BM} = F_{BM} * C_p^0 \quad (16)$$

where C_p^0 represents the purchase cost at base conditions. In order to estimate the bare module cost, C_{BM} , the bare module cost factor, F_{BM} , must be applied to ensure that the specific conditions of the equipment are met.

To ensure that this method is properly applied, one should follow a logical set of steps toward the estimated module cost of a determined piece of equipment. The process happens as follows:

1. Acquire the base cost, C_p^0 , for the desired piece of equipment from the corresponding chart or use Eq. (17), which fits the behavior of the cost of a series of instruments to their capacity parameter, in order to determine its base cost.

$$\log_{10} C_p^0 = K_1 + K_2 \log_{10}(C) + K_3 [\log_{10}(A)]^2 \quad (17)$$

K_1 , K_2 and K_3 , as well as the fitted charts for several pieces of equipment, can be found in Appendix A from Turton et al. (2012).

2. It is important to note here that the bare module factor, F_{BM} , can also be determined for base conditions and, in this case, it assumes the notation F_{BM}^0 , and the bare module cost is also assumed to be related to base conditions, C_{BM}^0 . In this work, the approach used considers Eq. (18) to calculate F_{BM} depending on the conditions of the system, operating at base conditions or not.

$$F_{BM} = [B_1 + B_2 F_P F_M] \quad (18)$$

This equation can be used for various types of heat exchangers, process vessels and pumps; however, it cannot be applied for all the pieces of equipment. B_1 , B_2 and F_M are tabulated values and can also be found in Appendix A from Turton et al. (2012). To account for pressure effects, the factor, F_P , can be calculated using

Eq. (19) for pressure vessels and Eq. (20) for all the remaining process instruments.

$$F_{P,vessel} = \frac{\frac{(P+1)D}{2[850-0,6(P+1)]}+0,00315}{0,0063} \quad (19)$$

$$\log_{10} F_P = C_1 + C_2 \log_{10} P + C_3 (\log_{10} P)^2 \quad (20)$$

In both cases, the pressure, P , is in barg, and the diameter, D , in meters. Values for C_1 , C_2 and C_3 are available for various pieces of equipment in Appendix A from Turton et al. (2012).

3. All the values presented by the authors correspond to a period between May and September 2001. The average CEPCI used was 397; therefore, as the final step, the estimated values must be updated using Eq. (7) and the CEPCI that corresponds to the year desired by the user.

3.2. Techniques' reliability

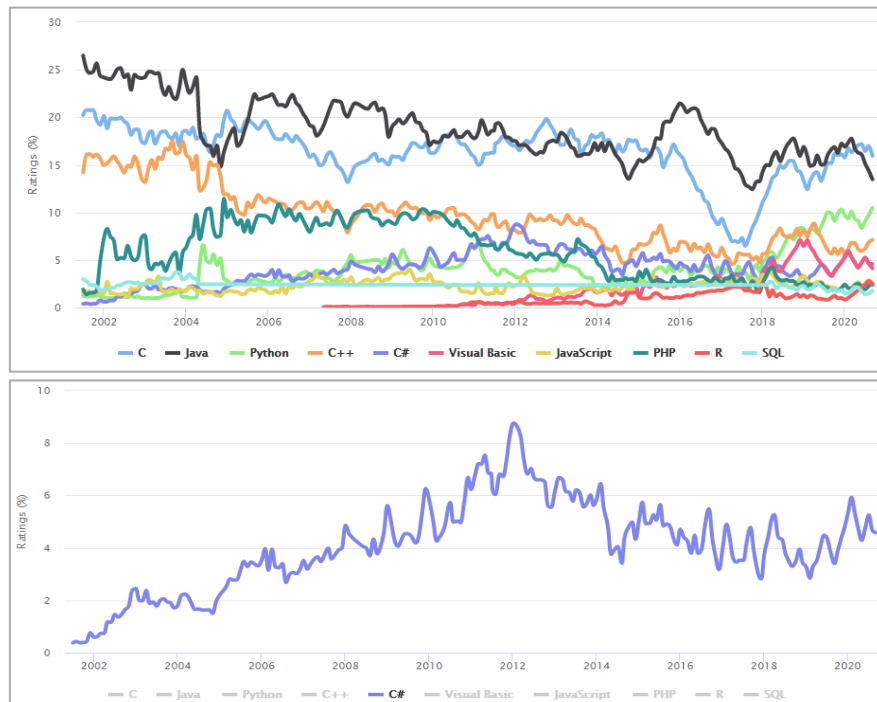
According to AACE international Recommended Practice 18R-97, the person responsible for the estimate will determine the cost estimate class based on the detailing of the project. The aforementioned estimation techniques were selected due to their extensive database and their popular application in research. The estimating models used in this work, even though are largely applicable, can mainly provide study or preliminary estimates (Class 5 and 4) reaching +50% in the upper boundary and -30% in the lower boundary.

3.3. Software development

Aiming to develop a solution that could work, mostly, on PCs that use Microsoft's Windows OS, the programming language chosen was C#. It is one of the most popular languages used nowadays, according to the TIOBE index. Being an object-oriented and high-level programming language, C# is limited only by the creativity of the developer. It can be used in dynamic websites,

development tools, applications for PC and smartphones, and even compilers. (NASER, S.S.A; AL-BASTAMI, B.G.H, 2017; LINGKANG, G. et al.; 2017).

Figure 3 - Programming languages ranking of 2020



Source: TIOBE Index, 2020.¹

In order to build an easily manageable solution for users, a graphical user interface (GUI) was developed using a .NET framework called Windows Presentation Foundation (WPF). The WPF associates functionalities from the XAML language to define and link graphical elements to C# and other .NET programming languages in order to create solutions and enhance the application capabilities (BURNS, S.F., 2018).

After analyzing every cost estimation method and all of their entries and equations, a structure for the development of the software was prepared. This structure follows the Model-View-ViewModel (MVVM) architectural pattern, which allows different features of the application to be programmed at the same time; therefore, user interface designers can work on the view while programmers can work on the functionalities of the software on the Model layer. The ViewModel functions as a bridge between the upper layer (VIEW), where the interaction with

¹ Available at: <<https://www.tiobe.com/tiobe-index/>>. Accessed on: October 1st, 2020.

the user happens, and the lower layer (MODEL), where all of the calculations happen (BURNS, S.F., 2018).

The software development process was later divided into three steps: Estimation engine, User Interface and, finally, Database connection:

3.3.1. Estimation engine

Aiming to accurately achieve values for the estimated cost for the majority of the instruments encompassed by the techniques presented in the methodology of this work, several files were created and coded using C# to perform the necessary calculations to acquire the final values.

The process to estimate the cost of each piece of equipment has its particularities in each of the techniques applied in this work. However, a similar structure was used in the classes pertaining to Guthrie's and Towler's factorial methods.

The Object-Oriented programming methodology was applied to the characteristics of each technique in order to create a logical structure that follows the Unified Modeling Language (UML). This UML class diagram holds the structure used to model the behavior for every equipment class developed. For instance, the reactor UML class diagram for Towler's factorial method can be organized as follows:

Equipment class	Equipment - Reactor
ATTRIBUTES	- <code>double</code> volume, n, custo,min,max; - <code>string</code> tipo, material; - <code>int</code> a, b;
METHODS	<pre> + ReatCostEst(); + Reatores(double volume, string tipo, string material); + getTipo(); + setTipo(string tp); + getVol(); + setVol(double vol); + getMaterial(); + setMaterial(string mat); </pre>

The same procedure was reproduced for the pieces of equipment summarized in Table (6) in each method:

Table 6 - Equipment classes developed for the estimation engine

Guthrie	Towler and Sinnott	Turton et al.
Compressor	Boiler	Heat exchanger
Furnace	Centrifuge	
	Compressor	
Heat exchanger	Crushers	
Heater	Crystallizer	
Pressure vessel	Evaporator	Pressure vessel
	Filters	
Pump	Furnace	Trays
	Heat exchanger	
Trays	Mixer	Pump
	Pressure Vessel	
	Pump and driver	
	Reactor	
	Tank	
	Trays	

The equipment classes developed, for each technique explored in this work, inherit the information about specific factors from a class that functions as a database, storing material, pressure, type and other specific factors that must be applied to the estimation process. Furthermore, in some specific cases, such as estimating the cost of a distillation column, the classes were coded to work together, sharing information and access privileges between themselves in order to allow the user to calculate the estimated cost of a specific piece of equipment.

3.3.2. User Interface

In this research, the elements explored in the process of developing a User Interface for the software were based on a framework created to assist the

development of applications for Windows OS. WPF was the framework selected to build the connection between the user and the code.

One of its major advantages when compared to other frameworks is that its features are programmed using a different language from the one used by the developer, which means that the classes developed to calculate the estimated values and the code that controls the interface are independent from one another, allowing programmers and designers to work in the same project simultaneously.

By using WPF, a specific pattern was applied to this project with the intention of facilitating the management of code. Model-View-ViewModel (MVVM) is a programming pattern developed by the same architect who developed the WPF, and its main purpose is to divide the project into defined layers, separating the user interface from the database and from the code that performs all the operations toward the cost estimate.

Using some WPF feature, such as data binding, the user interface was designed to allow communication between the user and the code. The detailed function and operation of the main windows developed are presented as follows:

3.3.2.1. MainWind

The initial window of the software, named *MainWind.xaml*, instructs the user to create a new project or to open a previous one through action buttons that will open dialog windows, which are native to the operational system, for the user to create the path to where the project archive will be stored or to select an older project to be edited or visualized.

All its functionalities were coded using XAML, and the communication with the other windows was developed in code-behind using C#.

3.3.2.2. EquipSelect

In the action of creating or opening an archive in (.CeT) format in the software, a new window is activated, the *EquipSelect.xaml*. In this window, several features were programmed to display and guide the user through the process of selecting a piece of equipment and the desired estimating technique. Labels were added to the windows in order to indicate the functionalities of each element displayed.

The cost estimation methods were inserted inside a *combobox*, a control that exhibits a list of elements in a collapsible box that reveals its content when clicked by the user. Once the estimation model is chosen, another action button is activated, indicating to the user that the program is ready to work on the desired equipment.

3.3.2.3. Equipment screens

Based on the selection of the equipment and model, different equipment screens will appear to the user. All of the developed interfaces have elements in common, such as the labels that identify the fields designed for the insertion of the equipment name, and also the identification of *comboboxes* that contain specific information of the type and material of construction for the selected equipment.

These screens were sorted by estimation technique since there are different information requirements for the same piece of equipment in different techniques.

3.3.3. Database connection

To enable the user to revisit former projects and also share information about a current project, a database connection was defined. Using the version 1.7.335 of the Sqlite-net-pcl open-source library, it was possible to develop a logic structure to store the data from the software.

The applied library is based on the SQL database language; therefore, a class was programmed to organize the information in a table with predefined columns, as shown below:

Id	Equip	Type	Material	Capacity	Value	ExibValue	CEPCI

The “Id” field was determined to function as a *PrimaryKey*, which means that at every iteration of the program, a unique value is associated with a piece of equipment. The *Autoincrement* command was also inserted in order to automatically assign a new value for new equipment.

3.4. Case study for validation of the software

Aiming to validate the study presented, information on operating process equipment was withdrawn from Appendix C of Turton et. al (2012), more precisely from “Project 5: Problems at the Cumene Production Facility, Unit 800”, in order to conduct a comparison between the cost estimated by the software developed and other popular programs and computational solutions for cost estimation.

In this section, the aforementioned authors exposed a PFD from a Cumene production process and discussed some strategies to guarantee that the plant continues functioning within the specifications. The pieces of equipment selected for the study case are the distillation column, T-801, with two heat exchangers, E-803 and E-804, the reflux drum, V-803, and, lastly, two centrifugal pumps, P-803 and P-804. All the pieces of equipment were considered to be constructed from carbon steel since the material seems to be compatible with the compounds of the process. The necessary data were withdrawn and exposed in Table (7).

The same conditions, when possible, were reproduced with CAPCOST, an excel add-in developed by Turton and collaborators, with Aspen Capital Cost Estimator, a cost estimation platform developed by AspenTech and, finally, with *Matche.com*, a website that provides engineering solutions including order-of-magnitude cost estimation for several instruments.

In addition to the information on the equipment design, the cost index applied to consider the influence of time and inflation was the yearly average CEPCI value of 607.5, which refers to 2019.

Table 7 – Study case data

Equipment	Description	Design data
T-801	Distillation Column	Diameter: 1.13 m Number of trays: 27 Tray spacing: 24 in
P-803	Pump (Centrifugal)	Flowrate: 2.7 liters/s Power: 2.4 kW
P-804	Pump (Centrifugal)	Flowrate: 3.74 liters/s Power: 1.0 kW
V-803	Reflux drum	Length: 4 m Diameter: 1.6 m
E-803	Heat exchanger (Shell and tube) – Total condenser	Heat exchange area: 151 m ²
E-804	Heat exchanger (Shell and tube) – Reboiler	Heat exchange area: 405 m ²

4. Results

This research proposes the development of an application that is able to apply different cost estimation models to common pieces of equipment used in chemical processes. In order to guarantee its functionality, the following steps will be taken: firstly, an analysis of the cost estimation models programmed into the project will be performed; secondly, a discussion will be conducted on how the product visually communicates with its users; and, finally, we will illustrate how it displays and stores the results of the cost estimation performed.

Furthermore, the case study discussion will determine if the techniques are capable of properly estimating the approximate purchase value for the selected equipment, and how CostApp's results compare with other popular solutions used in the field.

4.1. Analysis of the estimating modules programmed

Several classes were programmed in this work to perform the cost estimation procedures described by the techniques previously explored in the methodology section. In order to verify the performance of the code, applications of the techniques present in the literature were reproduced using coded procedures to assure their functionality.

4.1.1. Cost curve

The following table exhibits the information retrieved from Towler et al. (2013) of various pieces of equipment and their characteristics, as well as their estimated cost.

Table 8 - Equipment information from the literature

Equipment	Characteristics	Estimated cost
Distillation Column	Height: 30 (m) Diameter: 3 (m) Operating pressure: 10 (bar) Trays: 50 (sieve) Construction material: ss 304	\$3.227.150,00

Table 8 - Equipment information from the literature (*cont.*)

Equipment	Characteristics	Estimated cost
Heat exchanger	Type: U-tube Heat transfer area: 60 (m ²)	\$160.615,00
Heat exchanger	Type: Kettle reboiler Heat transfer area: 110 (m ²)	\$257.075,00
Pressure vessel	Type: Horizontal Volume: 3 (m ³) Operating pressure: 10 (bar)	\$121.600,00
Storage tank	Volume: 50 (m ³)	\$99.125,00
Pump	Type: Centrifugal Flow rate: 3.6 (m ³ /h)	\$42.848,00

Using the information from Table (7), the developed classes for each piece of equipment provide the following results:

Table 9 – Results retrieved from the programmed classes

Equipment	Characteristics	Estimated cost
Distillation Column	Height: 30 (m) Diameter: 3 (m) Operating pressure: 10 (bar) Trays: 50 (sieve) Construction material: ss 304	\$3.148.013,52
Heat exchanger	Type: U-tube Heat transfer area: 60 (m ²)	\$160.833,87
Heat exchanger	Type: Kettle reboiler Heat transfer area: 110 (m ²)	\$257.069,44
Pressure vessel	Type: Horizontal Volume: 3 (m ³) Operating pressure: 10 (bar)	\$120.116,44
Storage tank	Volume: 50 (m ³)	\$99.254,086
Pump	Type: Centrifugal Flow rate: 3.6 (m ³ /h)	\$45.552,63

The difference between the values determined by the authors and those provided by the software developed is very small, and it is explained by the fact

that Towler et al. (2013) approximate some of the parameters used when performing the determination of the estimated cost. In addition, the relative error between the literature and the software results does not exceed 6%, which shows that the estimation engine is working properly for this technique.

4.1.2. Guthrie

Following the same strategy, the application of Guthrie's estimation technique was chosen to verify if the code works properly to determine the estimate. The selected example was withdrawn from Gutierrez (2003) and the design information for the equipment, as well as the estimated cost, is presented in Table (10) below:

Table 10 - Design information for the Heat exchanger cost estimation

Equipment	Characteristics	Estimated cost
Heat exchanger	Type: Kettle Heat transfer area: 1500 m ² Construction material (Tube/Shell): Stainless steel/ Carbon steel Operating pressure: 400 psi Corresponding year: 2000	\$286.414,00

The same data were inserted in our software and the estimated cost was \$280.466,987. The relative error between the application and the literature case is only 2% - mainly caused by the fact that the author retrieved the base cost of the heat exchanger directly from its base cost chart - and the software, in order to ensure a more accurate value, uses a mathematical relationship based on the behavior expressed by the heat exchanger base cost chart.

4.1.3. Turton et al.

In order to analyze the performance of the code in the case of Turton's method, an example was extracted from Turton et al. (2012). In this example, the authors apply their model to estimate the bare module cost of a stainless steel tower in 2011 (CEPCI: 582). The design data is shown on Table (11).

Table 11 - Design information for the Towler and Sinnott cost estimation

Equipment	Characteristics	Estimated cost
Tower	Diameter: 3 m Length: 30 Operating pressure: 20 barg	\$7.550.300,00
Trays	Type: Sieve N° of trays: 40 Construction material: stainless steel	\$490.400,00

The same information was applied to the estimation engine coded, and the results acquired are summarized in Table (12).

Table 12 - CostApp estimation for estimation technique by Turton's et al.

Equipment	Characteristics	Estimated cost
Tower	Diameter: 3 m Length: 30 Operating pressure: 20 barg	\$7.644.241,55
Trays	Type: Sieve N° of trays: 40 Construction material: stainless steel	\$482.308,33

For each piece of equipment, the relative error does not exceed 2%, which shows a satisfactory behavior of the code written to apply the bare module cost technique to the solution produced by this work.

According to these results, it is possible to conclude that the difference between the examples extracted from the literature of the approaches explored in development of this research and the tests performed by our application using the same approaches is rooted in extrapolations and approximations made by the authors. The minor error identified in both cases proves that our application is consistent with the techniques applied.

4.2. User interfaces

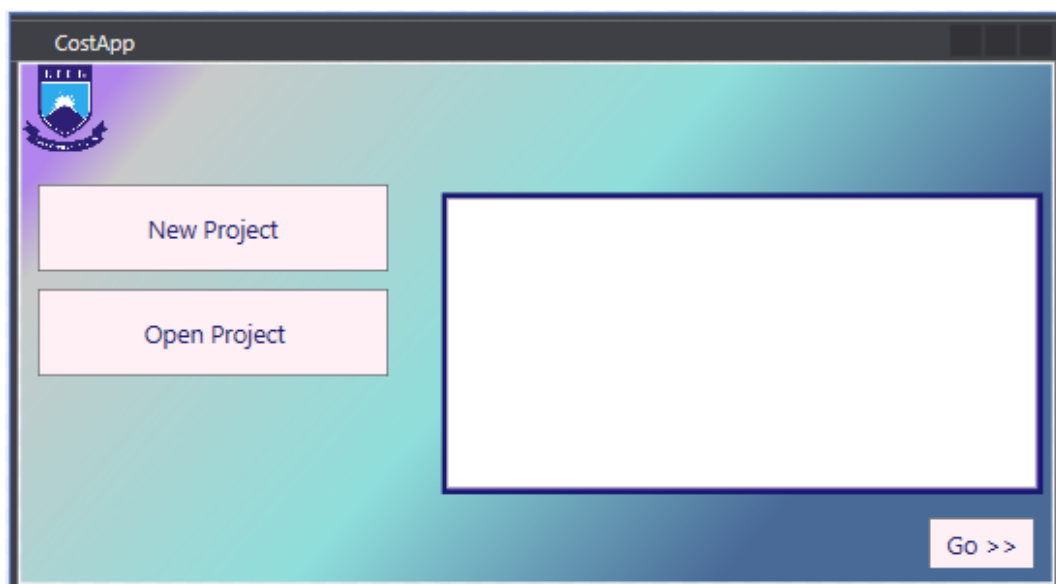
All user interfaces developed in this work were built using XAML and followed a pattern of colors, *textblocks* and positioning of buttons inside the developed windows. The software interface is composed of different windows and each one has a specific function. The window with the equipment and model options is the most important one since all major operations of the software are performed in it.

Individual windows were developed for each piece of equipment and divided into groups since the information needed to calculate the estimate varies according to the chosen technique. All of the built interfaces are essential for the process of properly guiding the user through the software functionalities. Such windows are described below:

4.2.1. Main window

The main window objective is to direct the attention of the user toward creating a new project or opening a previous one. Through the action buttons, the user can communicate with the operational system and dialog windows will appear; therefore, it is possible to navigate to a saved file or choose a path where a brand-new project will be stored.

Figure 4 - Main window of functionalities



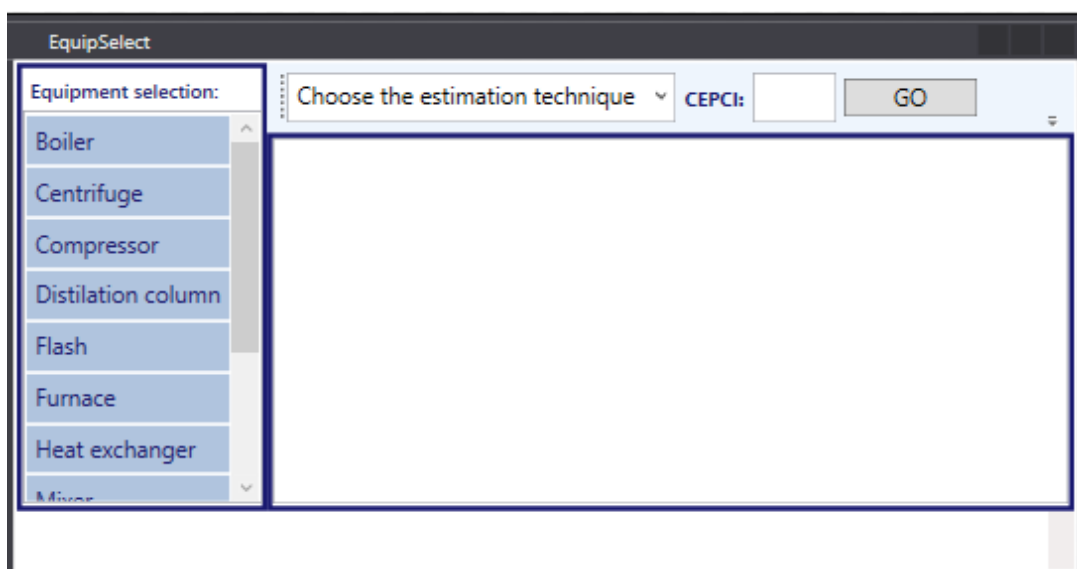
On the right side, there is a *viewbox* where the user can check the equipment inserted in the selected project and, finally, through the action button at the bottom right corner, a window will be loaded, from which the process of inserting or editing equipment and models will be possible.

4.2.2. Equipment and Model selection

The window presented below in Figure (5) works as a “control room” for the estimating process proposed in this work. Through such window, the user is able to select the desired equipment from the *listview* on the left; the model through which they want to perform the estimate from the *combobox* at the top; and in the center, the main information will be exhibited along with the estimated cost of all the pieces of equipment selected and adjusted by the user.

This command window allows the user to repeatedly choose any piece of equipment, even repeating the same piece of equipment, and estimate its cost through the techniques available. The action button on the right side of the *combobox* will allow the user to access the editing screen for the selected instrument and once they inform the necessary data, the cost estimate can be achieved.

Figure 5 - Window to edit or add new equipment



4.2.3. Equipment screens

There are particularities in each estimation method applied in this work and since they approach each piece of equipment through different parameters to determine their probable cost, each screen was developed to meet the specific needs of the chosen technique in order to accurately perform the cost estimate. It is possible to notice these specific features when analyzing the windows responsible for the heat exchanger cost estimation using Guthrie and Towler's factorial method.

Figure 6 - Cost estimation windows for Heat Exchangers

The screenshot shows a software window titled "TrocadorView" with a subtitle "Heat Exchanger". On the left side, there are four input fields: "Name:" (text box), "Type:" (dropdown menu), "Material:" (dropdown menu), and "Heat exchange area:" (text box with a dropdown arrow). On the right side, there is a "Cost Preview:" field which is currently empty. Below the "Cost Preview" field are two buttons: "Calculate" and "Save". A circular icon with a pulse line is positioned to the right of the input fields.

(a) – Cost Curve technique

The screenshot shows a software window titled "TrocadorView" with a subtitle "Heat Exchanger". On the left side, there are five input fields: "Name:" (text box), "Type:" (dropdown menu), "Material:" (dropdown menu), "Heat transfer area:" (text box with a dropdown arrow), and "Pressure:" (text box with the value "0" and a dropdown arrow). On the right side, there is a "Cost Preview:" field which contains the value "Di". Below the "Cost Preview" field are two buttons: "Calculate" and "Save". A circular icon with a pulse line is positioned to the right of the input fields.

(b) – Guthrie's technique

trocadorTurtonView

Heat exchanger


Name:

Type:

Material:

Pressure:

Heat transfer area:


 Cost Preview:

(c) – Turton's et al. technique

Comparing Figure (6.a), (6.b) and (6.c), it is possible to see that different fields were added to the second and third screens. The reason for this is that in order to be able to calculate the approximate cost of a heat exchanger, the chosen techniques need to calculate the pressure factor for the equipment, and it is only possible to determine this factor with the information about the operating pressure under which the exchanger would work. The same behavior is observed in the windows for cost estimation of pumps:

Figure 7 - Cost estimation windows for Pumps

Bomba


Pump

Name:

Type:

Material:

Flowrate:


 Cost Preview:

(a) – Cost Curve technique

The screenshot shows a software window titled 'bombaViewgut' with a blue background. At the top center, the word 'Pump' is displayed in a large, blue, underlined font. Below this, there are several input fields and dropdown menus: 'Name:' with a white text box; 'Type:' with a grey dropdown menu; 'Material:' with a grey dropdown menu; 'Pressure:' with a white text box and a grey dropdown menu; 'Temperature:' with a white text box and a grey dropdown menu; and 'CH factor:' with a white text box. To the right of these fields is a grey icon of a pump. Below the icon is a 'Cost preview:' label followed by a white text box. At the bottom right, there are two buttons: 'Calculate' and 'Save'.

(b) – Guthrie's technique

The screenshot shows a software window titled 'bombaTurtonView' with a blue background. At the top center, the word 'Pump' is displayed in a large, blue, underlined font. Below this, there are several input fields and dropdown menus: 'Name:' with a white text box; 'Type:' with a grey dropdown menu; 'Material:' with a grey dropdown menu; 'Shaft power:' with a white text box and a grey dropdown menu; and 'Pressure:' with a white text box and a grey dropdown menu. To the right of these fields is a grey icon of a pump. Below the icon is a 'Cost Preview:' label followed by a white text box. At the bottom right, there are two buttons: 'Calculate' and 'Save'.

(c) – Technique by Turton's et al.

All the screens developed are adapted to inform to the estimation engine the specific information required for the selected estimation method.

4.2.4. Information storage

Based on the Standard Query Language (SQL), the database used in this work was structured to hold information inserted by the user, calculated by the software and also some information from inside the code itself. Using the add-in SQLite on Visual Studio, it was possible to enable the features of the database inside the code and properly organize the data to be stored inside tables.

From Figures (8) and (9), taken thanks to other software, it is possible to notice how the programmed routine organizes the structure of the table that will store the data inserted and calculated by the software.

Figure 8 - Structure of the Database

Column	SQL Type	SQL Definition
Id	integer	"Id" integer NOT NULL
Equip	varchar	"Equip" varchar
Tipo	varchar	"Tipo" varchar
Material	varchar	"Material" varchar
Capacidade	float	"Capacidade" float
Valor	float	"Valor" float
DispCost	varchar	"DispCost" varchar
CEPCI	float	"CEPCI" float

Figure 9 - Example of data storage

Id	Equip	Tipo	Material	Capacidade	Valor	DispCost	CEPCI
Filtro	Filtro	Filtro	Filtro	Filtro	Filtro	Filtro	Filtro
2	Heatex	Floating head shell and tube	Carbon steel	80.0	159084.077812072	R\$ 159.084,08	545.3

The software code was written to properly separate each instrument through an individual identification parameter and populate each field with the respective values and information.

The “Equip”, “Tipo” and “Material” fields allow data of the “varchar” type to be inserted, which means that these fields will store information in text, in this case the name of the equipment, its type and construction material, respectively. The last field, named “CustoDisplay”, also stores information in text format; however, it is possible to see in Figure (9) that it stores numbers. This happens because in order to display the formatted value of the cost, it is necessary to convert the value of the cost from a number type to a text type in order to exhibit the formatted values.

Lastly, the “Capacidade” and “Valor” fields were designed to store the capacity parameter informed and the estimated cost, respectively.

4.3. Case study discussion

In order to compare the functionalities of the software built as a result of this work, a case study was performed using information gathered from Turton et al. (2012), which is shown in Table (6).

From the case study data, it was possible to estimate the cost for some industrial equipment using well-known computational tools in the chemical and cost engineering fields. The discussion on these estimates and their values is presented below.

Table 12 – Estimates for the Pumps

Equipment	P-803	P-804
CAPCOST (Bare module cost)	\$16,000.00	\$14,900.00
ACCE (Direct cost)	\$18,600.00	\$18,700.00
Matche.com	\$5,167.07	\$6,643.38
CostApp - Cost curve	\$36,218.98	\$37,062.35
CostApp - Guthrie	-	-
CostApp - Turton et al.	\$16,471.16	\$14,931.77

Based on the data presented in Table (12), it is possible to notice that the cost estimation for the pumps ranges from a lower value, given by *Matche.com*, to a higher value, given by the cost curve model on CostApp. This higher value can be explained by the fact that the cost curve technique applies HAND factors to its estimates in order to achieve a more accurate estimation.

There are still intermediate values for the cost estimation, which are the values provided by the CAPCOST add-in, AACE and CostApp's implementation of the bare module cost technique by Turton et al. CostApp and CAPCOST's estimates, both based on Turton's method, have almost equal values since both solutions apply the same methodology and parameters; however, it seems that in order to present more "round" results, CAPCOST performs some approximations, which could explain the deviation between its result and the one provided by CostApp.

Guthrie's technique could not be applied to this case since the necessary information to estimate pump cost was not found.

Table 13 - Estimates for the Heat exchangers

Equipment	E-803	E-804
CAPCOST (Bare module cost)	\$155,000.00	\$302,000.00
ACCE (Direct cost)	\$146,300.00	\$226,000.00
Matche.com	\$64,535.67	\$126,329.63
CostApp - Cost curve	\$224,515.57	\$465,769.13
CostApp - Guthrie	\$55,033.59	\$104,505.36
CostApp - Turton et al.	155,463.64	302,449.36

The estimated price for the heat exchangers is fairly similar between *Matche.com* and Guthrie's implementation, as well as in the case of CAPCOST, ACCE and Turton's method. Even though the cost curve method uses the same capacity parameter as the other techniques, its value is higher than the others. Nevertheless, the same behavior can be observed in the research conducted by Feng and Rangaiah (2011), in which the authors use another computational tool that also implements the cost curve methodology by Towler and Sinnott.

The estimated costs for the heat exchangers (E-803, E-804), provided by ACCE, CAPCOST, and by the cost curve model inserted in the solution developed, are in the same order of magnitude. Even though their results are quite distant in value, they maintain a similar cost growth behavior.

Table 14 – Estimates for the Reflux Drum

Equipment	V-803
CAPCOST (Bare module cost)	\$43,200.00
ACCE (Direct cost)	\$138,000.00
Matche.com	\$27,733.47
CostApp - Cost curve	\$60,434.44
CostApp - Guthrie	-
CostApp - Turton et al.	\$35,587.96

The reflux drum falls into the category of "pressure vessel", and this type of equipment requires a more careful design. The range of values, in this

particular case, could be explained by the fact that different factors and conventions were chosen by the authors of each method. The influence of corrosion, weld, geometry and also the equations applied to the vessel design could affect its overall estimate.

Table 15 – Estimates for the Distillation Column

Equipment	T-801
CAPCOST (Bare module cost)	\$154,000.00
ACCE (Direct cost)	\$305,700.00
Matche.com	-
CostApp - Cost curve	\$78,957.82
CostApp - Guthrie	\$347,757.17
CostApp - Turton et al.	\$136.633,30

The estimation process for the distillation column, in the majority of cases, is divided into the estimation of the vertical pressurized vessel and of the trays or packing. The cost behavior seen in Table (14) is similar to the behavior in Table (15) since both cases deal with pressurized vessels; however, in the latter case, the orientation of the vessel is vertical and there is also the associated cost of the trays.

Due to the orientation of the vessel, the cost estimate using Guthrie's technique was not possible for the column since the estimation engine only contains the class for vertical vessels. Furthermore, its estimate has the closest value to that of ACCE, which is an impressive result considering that ACCE applies a more detailed approach to its estimates.

Table 16 - Final budget for the case study

Software/Solutions	Budget
CAPCOST (Total module cost)	\$810,000.00
ACCE (Direct cost)	\$853,300.00
CostApp - Cost curve	\$902,958.29
CostApp - Turton et al.	\$780,613.88

In Table (16), the values for the complete budget, when possible, are shown. Comparing the total amount reached by CostApp - using the cost curve and Turton's methods - with ACCE and CAPCOST, it is possible to notice that even though the individual values for each piece of equipment are not the same, the estimated budgets have similar values, which indicates that the approaches inserted into the code as well as the software performance can provide reliable results and its use could, in the future, be as popular as the usage of CAPCOST and ACCE.

In the case of *Matche.com*, the website does not seem to consider any expenses, only providing a direct purchase cost which corresponds to the cost in 2014. However, to be able to fairly compare the estimates, the CEPCI for 2014, which is 576.1, was found and through Eq (7), the estimate was updated and presented in Table (12).

The individual values obtained from the CAPCOST add-in are free of any additional factors. On CAPCOST, the factor that considers expenses with freight, installation, workforce, taxes, etc., is applied to the sum of the estimates of all pieces of equipment, while in the CostApp's cost curve model, the factors that account for these expenses are applied individually to each piece of equipment estimated.

The cost estimated by ACCE is very close to the estimate provided by CAPCOST; however, this time, it was not possible to consider the effects on inflation on ACCE since the program does not allow the insertion of cost indices.

5. Conclusions

The computational application of cost estimation models is present in the most popular software used in the chemical engineering field, showing that estimating costs is essential when developing, analyzing or optimizing chemical processes. This work aimed to produce a tool that could add a new and platform-independent application to the cost engineering field in order to bring forward new methodologies in a way that could be easily manageable and accessible.

The software developed is based on more than one estimation technique from the literature; therefore, the user can choose which method better adapts to the precision of the desired estimate since the techniques explored in this work and in other solutions, such as *Matche.com*, are not capable of estimating a large variety of equipment from the chemical industry.

The results extracted from CostApp, when compared with values provided by CAPCOST, Aspen Capital Cost Estimator and from *Matche.com*, revealed similar values regarding heat exchangers. Even though for some pieces of equipment the margin is greater, most values are in the same order of magnitude, which shows that CostApp can provide reliable cost estimation information and could be used depending on the scenario and precision needed. Since it is based on academic cost estimation approaches that can reach a Class 4 status, its estimates are within a $\pm 40\%$ accuracy.

Besides being developed in an open-source language, the computational solution produced has expansion capabilities and can also be installed in other operational systems. The versatility of the software could be attractive for students and developers from the field who are searching for opportunities to develop new solutions.

The development of solutions such as CostApp could benefit the planning or the analysis of chemical processes. Similar technologies could be programmed to function with other commonly used methodologies in process design, optimizing the time and work previously applied to them. In addition, with the introduction of industry 4.0 tools, such as Big Data or machine learning, it is possible to forecast scenarios, thus ensuring better management and planning of operating conditions.

Lastly, the experience of developing software inside the chemical engineering and cost estimation field raises a concern regarding the education of young professionals, who are currently facing the fourth industrial revolution, about programming and data analysis. The development of this work could set a precedent for further discussions on how to prepare engineers to deal with the advancements so often presented by computer scientists and the technology industry.

REFERENCES

AACE International Recommended Practice No. 18R-97. COST ESTIMATE CLASSIFICATION SYSTEM – AS APPLIED IN ENGINEERING, PROCUREMENT, AND CONSTRUCTION FOR THE PROCESS INDUSTRIES. Revised in March 2016.

Boehm, B., Abts, C. & Chulani, S. **Software development cost estimation approaches — A survey**. *Annals of Software Engineering* 10, 177–205 p. 2000. <https://doi.org/10.1023/A:1018991717352>

BOJORGE, N. I. R., LEITE, J.P., BELTRÃO, M. J. C., CHEBAR, I. E., **AVALIAÇÃO PRELIMINAR DO IMPACTO DE SOFTWARES DE SIMULAÇÃO NO ENSINO DAS ENGENHARIAS QUÍMICA E DE PETRÓLEO**. *ENGEVISTA*, v. 16, n. 1, p.28-40, March 2014.

CLOUGH, D. E. **ChE's Teaching Introductory Computing to ChE Students - A Modern Computing Course with Emphasis on Problem Solving and Programming**. American Society for Engineering Education Annual Conference & Exposition. 2002.

COKER, A. K. **Ludwig's Applied Process Design for Chemical and Petrochemical Plants**. 4th ed. USA: Gulf Professional Publishing. 1024p. 2007.

EPE (Empresa de Pesquisa Energética). **Compilação de Correlação de Custos de Equipamentos**. *Instalações Industriais de Gás Natural*. Ministério de Minas e Energia. Governo Federal. 24 de agosto de 2018.

GARRET, D. E. **Chemical Engineering Economics**. 1st ed. New York: Van Nostrand Reinhold. 1989.

GUTIÉRREZ, Arturo Jiménez. **Diseño de Procesos en Ingeniería Química**. España: Editorial Reverté, 2003. 272 p.

HAND, W.E. **From Flow Sheet to Cost Estimate**. *Petroleum Refiner*, Vol. 37, pp. 331-334, September 1958.

HUMPHREYS, K. K. **Project And Cost Engineer's Handbook**. 4th ed. New York: Marcel Dekker. 2004. 360p.

HUMPHREYS, K. K. **Project and Cost Engineers' Handbook**. 4^a ed. New York: CRC Press. 2004. 360p.

IBRAHIM, D. **Engineering simulation with MATLAB: Improving teaching and learning effectiveness**. *Procedia Computer Science*. v. 3, 853-858 p. 2011. <https://doi.org/10.1016/j.procs.2010.12.140> .

LEMMENS, S. **Cost Engineering Techniques and Their Applicability for Cost Estimation of Organic Rankine Cycle Systems**. *Energies*, v.9, no. 07, p 485, 2016.

MAO, Z. YANG, C. **Computational chemical engineering – Towards thorough understanding and precise application**. *Chinese Journal of*

Chemical Engineering. v. 24, Issue 8, 945-951 p. August 2016.
<https://doi.org/10.1016/j.cjche.2016.04.037>

MORAN, S. **An Applied Guide to Process and Plant Design**. Waltham: Butterworth-Heinemann, 2015.

PATLE, D. S., AHMAD, Z., RANGAIAH, G. P. **Operator training simulators in the chemical industry: review, issues, and future directions**. Reviews in Chemical Engineering, v. 30, Issue (2), 199-216 p. (2014).
<https://doi.org/10.1515/revce-2013-0027>

PETERS, M.S., TIMMERHAUS, K.D. **Plant Design and Economics for Chemical Engineers**. 4^a ed. McGraw-Hill. 1312p. 1991.

PUTRA, G. A. S., TRIYONO, R. A. **Neural Network Method for Instrumentation and Control Cost Estimation of the EPC Companies Bidding Proposal**. Procedia Manufacturing. v. 4, 98-106 p., 2015.
<https://doi.org/10.1016/j.promfg.2015.11.019>.

ROY, R. **Cost Engineering**. Journal of Engineering Design. v. 19, 97-98 p. May 2008. <https://doi.org/10.1080/09544820701868221>.

SANTOS, Moisés Teles; VIANNA JR., Ardson S.; LE ROUX, Galo A.C. **Programming skills in the industry 4.0: are chemical engineering students able to face new problems?** Education for Chemical Engineers, v. 22, 2018, Pages 69-76, ISSN 1749-7728, <https://doi.org/10.1016/j.ece.2018.01.002>.

SEIDER, W.D., SEADER, J.D., LEWIN, D.R., WIDAGDO, S., GANI, R., NG, K. M. **Product and Process Design Principles: Synthesis, Analysis, and Evaluation**. 4th ed. Hoboken: John Wiley & Sons, 2016.

SHABANI, M. R. **Suitable Method for Capital Cost Estimation in Chemical Processes Industries**. 2015. <https://doi.org/10.13140/RG.2.1.1545.7762>

SHEKHAR, S. KUMAR, U. **Review of Various Software Cost Estimation Techniques**. International Journal of Computer Applications. v. 141, no.11, May 2016. <https://doi.org/10.5120/ijca2016909867>

SINNOTT, R., TOWLER, G. **Chemical Engineering Design: Principles, Practice and Economics of Plant and Process Design**. 2^a ed. Waltham: Butterworth-Heinemann, 2013.1320 p.

SMITH, P. **Project Cost Management – Global Issues and Challenges**. Procedia - Social and Behavioral Sciences. v. 119. 485-494 p. March 2014.
<https://doi.org/10.1016/j.sbspro.2014.03.054>.

SMITH, R. **Chemical Process Design Integration**. Essex: John Wiley & Sons, 2005.

SYMISTER, O. J. **An Analysis of Capital Cost Estimation Techniques for Chemical Processing**. 2016. 65 p. Dissertation (Master of Science in Chemical Engineering) - Graduate School of Florida Institute of Technology, Melbourne, Florida, 2016.

TURTON, R., BAILIE, C.R., WHITING, W.B., SHAEIWITZ, J. A., BHATTACHARYYA, D. **Analysis, Synthesis and Design of Chemical Process**. 4^a ed. EUA: Prentice Hall. 2208 p. 2012

ULRICH, G. D. **A Guide to Chemical Engineering Process Design and Economics**. John Wiley & Sons. 1st ed. February 1984.

VAN AMSTERDAM, M.F. **Factorial Techniques applied in Chemical Plant Cost Estimation: A Comparative Study based on Literature and Cases**. 2018. 159 p. Dissertation (Master of Science in Chemical Engineering) - Faculty of Applied Sciences - Delft University of Technology, 2018.

WECHSUNG, A. OLDENBURG, J. YU, J. POLT, A. **Supporting Chemical Process Design under Uncertainty**, *Brazilian Journal of Chemical Engineering*, v. 27, n. 03, pp. 451 – 460, Julho - Setembro, 2010.
<https://doi.org/10.1590/S0104-66322010000300009>