

MANUFACTURING COST MODEL FOR HEAT EXCHANGERS OPTIMIZATION

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ABSTRACT

In the field of shell and tube heat exchangers traditional costing methods rely on simple parametric functions. Such correlations are usually based on the sole overall heat transfer surface, and are applicable to traditional equipment configurations only, and in limited size ranges, to estimate the equipment purchase price. This makes them unsuitable for utilization as an economical design tool, particularly when the equipment configuration is not standard, or when the manufacturer uses proprietary manufacturing processes, and in case computerized design optimization procedures are adopted. In order to provide a more precise costing approach, to be used during the design phase, in this paper an analytical – generative cost estimation procedure for shell and tube heat exchangers is developed, based on detailed geometrical features and manufacturing processes of the equipment. It can also be used for precise cost estimation during competitive bidding in make-to-order manufacturing context. In the paper existing cost estimation methods are reviewed and criticized at first. The new mathematical model for heat exchanger manufacturing cost estimation is developed and a parametric analysis is carried out showing that an optimal length-to-diameter ratio exist. Then numerical examples are included detailing the relative magnitude of cost items and showing the superiority of the suggested method in optimized design of heat exchangers when compared to traditional methods. Results show that exchangers configurations obtained according to this new costing procedure are cheaper than optimal configurations obtained resorting to traditional parametric costing methods.

KEYWORDS

Shell and tube heat exchanger, cost function, economic optimization, cost estimating.

1. INTRODUCTION

Cost estimation is a major activity during new products development since a large part of the product life-cycle costs are defined during the design stage (Dewhurst and Boothroyd, 1989). Moreover, the capability of rapidly and correctly estimating manufacturing costs for bidding purposes is critical for engineering-to-order manufacturers of non standard equipment with customer-defined designs and specifications (Kingsman et al., 1996). In this case, a cost overestimation implies a non competitive bid causing customer loss, while underestimating the cost leads to winning a contract but incurring a financial loss, thus determining the so called "curse of the winner". Furthermore, in both the preliminary and detailed design phases, being able to estimate future costs before the actual production takes place, allows cost-based decision making, and enables designers to assess the economic effects of their choices before product architecture or manufacturing methods are finalized, thus implementing a concurrent engineering approach allowing early economic justification (Noble and Tanchoco, 1990), economic evaluation of design decision (Oh and Park, 1993) and design for producibility assessment (Elgh and Cederfelt, 2007). Finally, when engineers try to define the architecture of a product by changing the values of design parameters, so that the investment and operating costs are minimized, they often rely on sophisticated numerical optimization methods, and the lack

of precise cost estimation techniques able to capture the effects of design changes severely impairs the effectiveness of such an optimization process.

A typical case of engineering-to-order equipment where cost-optimal design is important, is the field of heat exchangers manufacturing, considering their functional importance and widespread utilization in process plants.

In recent times a renewed interest in the optimal design of heat exchangers has been witnessed in the literature. This corresponds to the availability of new numerical optimization techniques, such as genetic algorithms (GA), able to handle a large number of design parameters including both discrete and continuous variables (Caputo et al., 2008). In greater detail, Tayal et al. (1999) suggested a methodology based on a command procedure to run the HTRI commercial design program iteratively coupled to a GA or a Simulated Annealing optimization engine to optimize design of heat exchangers. Ponce-Ortega et al. (2009) use a GA and the Bell-Delaware sizing method to minimize the total annual cost of shell and tube heat exchangers. Şahin et al. (2011) instead use the Artificial Bee Colony (ABC) algorithm to minimize the total discounted cost of the equipment. Amini and Bazargan (2014) as well as Sanaye and Hajabdollahi (2010) adopt the ϵ -NTU approach for computing heat transfer rates and the Bell-Delaware procedure to size the heat exchanger, exploring the Pareto frontier of efficiency vs total cost resorting to a GA. Hilbert et al. (2006) use parallel GA to carry out a multi-objective optimization of exchanger geometry. Even Fettaka et al. (2013) frame the GA-based design problem as a multiobjective optimization one, attempting to minimize simultaneously surface area and pumping power. Ravagnani et al. (2009), Patel and Rao (2010), and Lahiri et al. (2012) adopt a Particle Swarm Optimization (PSO) method showing that it can be as effective as a GA. Azad and Amidpour (2011) and Yang et al. (2014) define an objective function utilizing constructal theory and optimize it resorting to GA. Babu and Munawar (2007) use Differential Evolution (DE) algorithm to minimize the heat transfer area of shell and tube heat exchangers. Costa and Queiroz (2008) minimize exchanger's surface area by using an iterative procedure to explore the design space along the tube count table. Fesanghary et al. (2009) use global sensitivity analysis (GSA) and harmony search algorithm (HSA) in comparison with GA. Guo et al. (2009a) use GA coupled with an objective function representing the synergy between the velocity field and the heat flow. Guo et al. (2009b) use a GA to minimize the dimensionless entropy generation rate. Hadidi and Nazari (2013) adopt the biogeography-based (BBO) algorithm which mimics population migration across diverse habitats to design heat exchangers, in comparison to GA, PSO and ABC. Hadidi et al. (2013), instead, develop an economic optimization model based on imperialist competitive algorithm (ICA). Lahiri and Khalfe (2014) adopt both hybrid DE and Ant Colony Optimization techniques. Mariani et al. (2012) use a modified quantum particle swarm optimization (QPSO) method, to optimize shell and tube heat exchangers, and compare results to GA, PSO, and classical QPSO. Ravagnani and Caballero (2007) as well as Onishi et al. (2013) develop mixed-integer non-linear programming models to optimize shell and tube exchangers. Rao and Patel (2013) use a Teaching-learning-based optimization (TLBO) method, to mimic the natural phenomenon of teaching-learning process in heat exchanger design. Serna and Jiménez (2005) develop an analytical procedure for heat exchanger optimization based on Bell-Delaware design method and a compact formulation that relates the shell-side pressure drop with the heat exchanger area and the heat transfer coefficient.

However, most of these sophisticated approaches still rely only on very simplified correlations to build a cost-related objective function. Almost always, in fact, the equipment capital investment is estimated referring only to the exchanger surface area, and resorting to statistical correlations of market data. Since such investment cost functions are not dependent on the construction arrangement of equipment, or on the actual manufacturing operations, the possibility of an effective design optimization is thus questionable. This justifies why some scholars are skeptical about the use of precise optimization methods when applied to heat exchanger design, owing to the inherent fuzziness of the problem given the uncertainty in operating conditions and in the adopted design correlations (Bell, 2000).

In order to contribute to a solution of this problem, in this paper a manufacturing-based detailed cost estimation model for shell and tube heat exchangers is developed, to be utilized for both design optimization and bidding purposes.

In the paper, following a literature review and a description of traditional cost estimation techniques, the heat exchangers manufacturing process is described. An analytical-generative costing model based on the actual manufacturing process is then developed. A sensitivity analysis is carried out to demonstrate how the total equipment cost is sensitive to design changes. Finally, an application example is provided to compare the proposed costing method with the traditional one.

2. A REVIEW OF HEAT EXCHANGERS COSTING METHODS

Stewart et al. (1995) provide a detailed discussion of the entire cost estimating process. However, quantitative cost estimating methods are usually classified into statistical models, analogous models or analytical - generative models (Niazi et al., 2006). Statistical methods utilize regression models to identify the causal links and correlate costs and product characteristics in order to obtain a parametric function with one or more variables (Foussier, 2006). Nevertheless, artificial neural networks (ANN), being universal regression methods, have been also employed in cost estimating thanks to their ability to classify, summarize and extrapolate collections of data (Bode, 2000). An advantage of ANN is that they can effectively extrapolate and generalize because an input-output mapping is allowed without understanding the functional relationship between variables. However, ANN require a large set of training cases. In many circumstances ANN also showed superior performances respect traditional parametric methods (Mason and Smith, 1997). However, the cost estimation accuracy of ANN and their possible superiority respect parametric correlations strongly depends on the the structural properties of the network as investigated by Wang et al. (2000) and Wang (2007). ANN have been succesfully applied to cost estimating of process vessels (Caputo and Pelagage, 2008), mechanical components in the automotive industry (Cavalieri et al., 2004), mechanical processing operations (Wang and Stockton, 2001), heat exchangers (Duran et al., 2009), and even assembly systems (Shtub and Zimmermann, 1993).

The main drawback of statistical models is that they do not consider the characteristics of the production process or do not show the details of the cost structure but, rather, just establish an overall correlation between the total manufacturing cost and some cost-driving product characteristics (i.e. variables related to the product configuration or physical characteristics such as weight, size etc.). However, this requires that cost influencing product attributes should be known in advance and that the models can not be utilized for generative design when new manufacturing technologies are introduced. Furthermore, owing to the low level of detail, they usually do not allow a cost-based comparison between alternative product architectures. Finally, they require historical data which may be lacking. Nevertheless, statistical models have the advantage of not requiring a detailed definition of the single manufacturing process phases, which is appreciated when few products information are available, or when it is not possible to carry out a detailed product design in advance.

Analogous methods, instead, identify a similar product, and reuse the cost information to estimate the future cost by analogy, adjusting the cost for the differences between the products. Analogous models thus infer a similarity in the cost structure from a functional or geometrical similarity among products features. The strength of the similarity is proportional to the correspondence of the relevant characteristics (Layer et al., 2002), measured, for instance, as the distance between the points of a multi-dimensional features space. Analogous models have drawbacks similar to statistical methods, and are only as reliable as the capability of correctly identifying the differences between the studied product and the reference one. Alternatively, case based reasoning (CBR) and expert systems also rely on similarities between products to generate estimates and are effective in case of modular products with variants. CBR costing systems have been compared to parametric techniques by Duverlie and Castelain (1999) and even associated with AHP decision making techniques (An et al., 2007).

Analytical - generative methods are the most accurate in that they try to depict the actual product creation process through its decomposition into single manufacturing operations. Specific models analytically estimate the cost of each processing phase attributing a monetary value to the resources consumption on the basis of the technical parameters characterizing the operation. A bottom-up approach is then utilized to properly aggregate the costs incurred during the process of fabrication through summation of each cost item. A detailed model uses estimates of labour time and rates, material quantities and prices to estimate the direct costs of a product or activity, while an allocation rate is used to allow for indirect/overhead costs. Therefore, a detailed costing estimate results from a generative process plan which also allows specific cost drivers to be identified. In so doing alternatives to adjust products cost can be derived and trade-offs can be examined. Process oriented methods often include direct integration with CAD models to extract cost-driving geometrical product features (Ou-Yang and Lin, 1997; Wierda, 1991) or rely on data bases of standard times, cost rates and best-practice manufacturing methods, which may be integrated with computer-aided process planning software and knowledge-based methods (Shehab and Abdalla, 2002a,b). In this respect, Elgh (2007) develops a costing method based on process plans and integrated in an automated product design methodology, while Geiger and Dilts (1996) adopt a Group technology based approach for parts

classification and costing. Analytical techniques even form the basis of Design-for-Manufacturing methods, and provide detailed models for single technological processes (Boothroyd et al., 2011; Poli, 2001). However, analytical models require a larger amount of information, and are more time consuming as they require a detailed design of the product and processes knowledge. Overall, a multi-objective methodology to choose between available costing techniques has been suggested by Caprace and Rigo (2009).

Available cost models for heat exchangers, mainly belong to the first two of the above cited categories. Presumably this is a result of their standardized structure and fairly simple configuration or a consequence of their wide utilization in the fields of chemical engineering and process industries where parametric equipment costing methods are historically well established. However, the accuracy of such models is often quoted in the $\pm 10\%$ to $\pm 30\%$ range. The basic parameter involved in cost correlations for heat exchangers is the heat transfer area, which is an effective indicator of the equipment size. Simple power law cost function based on the exchanger surface area have been developed, for instance, by Hall and compiled in (Hall et al., 1990) and in (Taal et al., 2003). An example of a cost function for stainless steel exchangers is given as

$$C_E = 13324 + 431 \cdot A^{0.91} \quad (1)$$

where C_E is the capital investment (€), to be intended as FOB cost, while A is the surface area (m^2). Respect the original Hall equation this has been updated here on the basis of the CPI cost index, and the currency changed from \$ to €. Different equations were developed by Hall for other combination of materials (carbon and stainless steel), size ranges and exchanger types (U-tube, fixed head, floating head). For sake of completeness, and for the convenience of readers interested in parametric costing methods, Appendix I summarizes analytical expressions for a number exchangers cost correlations originally provided by Hall et al. (1982) in graphical form. A compilation of parametric cost correlations for heat exchangers is also provided by Rakonjac et al. (2012).

More precise methods attempt to correct the basic surface-related estimates through multiplication with some application-dependent factors. This approach can be regarded as an hybrid of parametric-statistical and analogous methods. As an example Corripio et al. (Corripio et al., 1995) define the base cost of a standard type of heat exchanger (carbon steel construction material, internal pressure < 690 kPa, floating head, surface area comprised between 13 and 1114 m^2) as,

$$b = e^{[8.551 - 0.30863 \ln(A) + 0.06811 (\ln(A))^2]} \quad (2)$$

while the cost of the actual exchanger is $C_E = b F_d F_p F_M$, being F_d the correction factor accounting for the exchanger type, F_d the correction factor accounting for the actual operating pressure, and F_M the construction materials factor. Such corrective factors, in turn, depend on exchange area and the application range through specific correlations. In a similar manner, Seider et al. (Seider et al., 1999) propose a cost function for the base case exchangers (surface area between 14 m^2 and 1100 m^2 , carbon steel material, $\frac{3}{4}$ (in) tubes with pitch to diameter ratio of 1.25, length of 6.1 m and operating pressure up to 6.8 bar) as

$$C_B = e^{\{K_1 - K_2 [\ln(A) + K_3 (\ln A)^2]\}} \quad (3)$$

and compute the actual equipment cost as $C_E = C_B F_M F_L F_P$, where F_M is a material corrective factor, F_L is the exchanger length corrective factor, and F_P the operating pressure corrective factor, K_1 and K_2 some constants factors.

Turton et al. (1998) provide costing correlations for carbon steel shell and tube exchangers operating at ambient pressure (in 1996 dollars) in the form

$$\log_{10} C_p = K_1 + K_2 \log_{10} A + K_3 (\log_{10} A)^2 \quad (4)$$

while the capital investment for an exchanger of different material and operating at higher pressure is

$$C_E = C_p (B_1 + B_2 F_M F_P) \quad (5)$$

where the pressure factor is given by $\log_{10} F_P = C_1 + C_2 \log_{10} P + C_3 (\log_{10} P)^2$, with P the operating pressure (bar gauge) while values for $K_1, K_2, K_3, C_1, C_2, C_3, F_M, B_1, B_2$ can be found in the original reference.

A further evolution of parametric-analogous approach is the Purohit method which represents one of the most detailed and sophisticated heat exchangers costing estimation technique available to date. It has an error margin lower than $\pm 15\%$ (Purohit, 1982). The method applies to a number of exchanger types: fixed sheet, U-tube, split ring floating head, pull-through floating head. It is valid for shell diameter comprised between 0.3 and 3 m, length comprised between 2.44 and 11 m, tubes diameter between $\frac{3}{4}$ " and 2", from 1 to 8 tube passes, shell side and tube side fluid pressure from 6.8 to 190 and 170 bar respectively. The model is based on a reference carbon steel heat exchanger 6.1 m long, having 1 or 2 tube passes, and an operating pressure lower than 10 bar. The assumed cost of the reference exchanger, based on correlation of US market data for 1982, is

$$b = \left[\frac{6.6}{1 - e^{[(7-D_s)/27]}} \right] p f r \quad (6)$$

where D_s (in) is the internal shell diameter, p is a corrective factor accounting for tubes external diameter, pitch and arrangement, while f and r are corrective factors related to the type of front and rear TEMA heads (Purohit, 1982).

Then the following correction factors C_i are factored in, namely, C_L (tube length correction), $C_{N_{tp}}$ (tube passes, when greater than 2), C_{PS} (shell side pressure), C_{PT} (tube side pressure) correction when internal pressure is greater than 10 bar, C_G (tube gage, when tubes are > 14 BWG), construction material correction factors (if different from carbon steel) for tubes (C_{MT}), shell (C_{MS}), channel (C_{MC}), tube-sheets (C_{MTS}). All of these correction factors are estimated through empirical correlations based on some constructive details of the equipment. Then the total 1982 estimated cost is

$$E_C = b \left(1 + \sum_i C_i \right) A \quad (7)$$

Another frequently adopted method is to relate equipment capital cost to its weight, as $C_E = \exp [A + B \ln(W)]$, with W (kg) the equipment weight (Shabani and Yekta, 2006). Instead, when only an order of magnitude estimate is sought, then one can refer to industrial cost directories which provide specific cost data (\$/ft², \$/lb, \$/ft) for exchangers of various size ranges (Compass International Consultants, Inc., 2014). Often manufacturers utilize proprietary tables or graphs relating exchanger weight $W [A]$ (kg) to its surface area A (m²) resulting from equipment sizing. Another set of graphs then relates specific cost $C_S[W]$ (\$/kg) to equipment weight, so that the final cost is estimated as $C_E = C_S[W] W[A]$.

Finally, as previously cited, even ANN techniques have been recently applied to heat exchanger cost estimation (Duran et al., 2009).

3. CRITICISM OF HEAT EXCHANGER COSTING BASED ON STATISTICAL CORRELATIONS FOR DESIGN PURPOSES

All of the above approaches, although widely utilized, are not suited for precise cost estimation during detailed design because,

- are obtained referring to a specific base case or are generated from statistical correlation of cost of exchangers having specific standard architectures, which may be different from the architecture of the specific heat exchanger to be designed;
- do not explicitly include manufacturing related variables or the detailed geometrical features characterizing the equipment architecture. Thus are not responsive to changes of design variables values when the same surface area is maintained, and are not utilizable for design purposes. For instance, available correlations are not sensitive to the choice of shell or tubes diameter, which heavily impacts on equipment cost;
- do not reflect actual manufacturing cost but rather the purchased equipment cost (or FOB cost), which is

influenced by market scenarios;

- are only valid in a specific and often narrow size range (for instance, Hall's correlations generally apply to surface areas lower than 140 m²);
- owing to the large error margin of the cost estimate do not allow comparison of alternative equipment architectures or comparison of equipment with small size differences;
- may not be available for all material classes or special operating conditions;
- are only precise at the time they are built, but when estimation is carried out at a different time costs need to be escalated resorting to cost indices to account for inflation and changes in market scenarios. However, cost indices only describe market price dynamics but can not reflect technical innovations and changes in manufacturing processes. Thus it is advisable not to use cost indices over time spans greater than a few years, while most of the available parametric correlations are more than 30 years old.

Finally, even if parametric correlations in general are quoted with an uncertainty range of 10% to 30%, different authors report correlations giving radically different cost estimates for equipment in the same size and pressure range as well as construction material. This makes the estimate unreliable. For instance, Figures 1 to 3 compare shell and tube exchangers cost estimates using some of the equations provided by Rakonjac et al. (2012) for different classes of construction materials over comparable size and pressure ranges. Original cost equations were escalated to year 2012 resorting to Chemical Engineering Plant Cost Index (CEPCI) and expressed in €. This demonstrated the wide uncertainty associated to this estimation method (cost differences range from about 60% to 80%) when correlations from different authors are used. The same discordance is also observed when comparing the output of commercial state-of-the-art cost estimation software which, nevertheless, are always based on parametric correlations (Feng and Rangaiah, 2011).

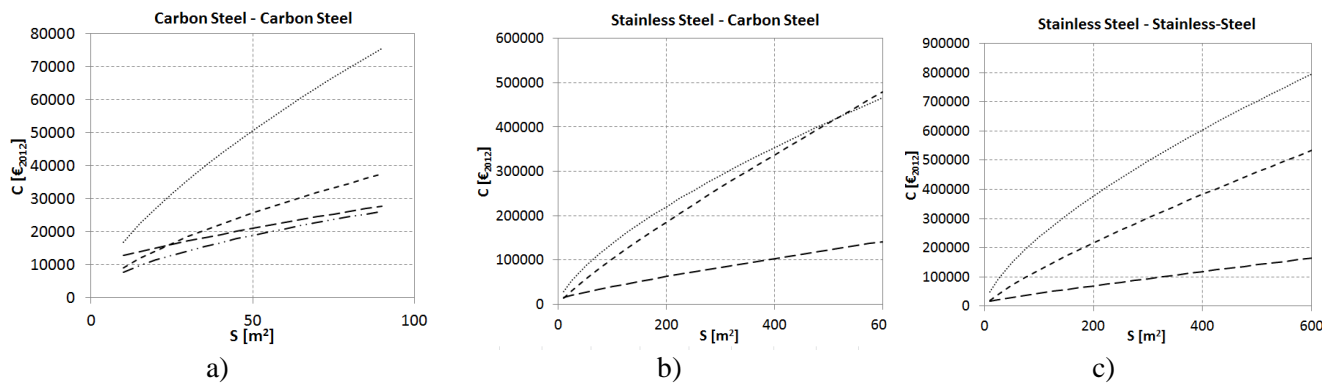


Figure 1. Comparison of heat exchangers parametric cost estimates: a) carbon steel exchangers; b) carbon steel / stainless steel exchangers; c) stainless steel exchangers.

Thus, resort to parametric correlations is only justified when scarce product information are available and when just a quick order-of-magnitude estimate is needed from the perspective of the buyer. This is not the case from the perspective of the equipment designer during the design phase, when equipment details are known because are in the process of being defined, and when cost implications of design alternatives are to be assessed.

Parametric correlations in particular are inadequate to be used in conjunction with computer-aided heat exchanger design procedures or with numerical equipment optimization algorithms. In fact, the algorithm may choose equipment configurations different from the standard configuration used to build parametric correlations, or the economic objective function may not be sensitive to design changes operated by the algorithm. This is especially critical when excessively simplified cost functions, such as Hall correlations (i.e. like Eq. 1), are used as a basis to define objective functions in numerical design optimization procedures, as often happens. The fact that cost correlations based on the sole surface area or on similarity issues are not suited for design optimization routines becomes obvious if one considers that exchangers having the same surface area (i.e the same cost according to heat transfer area-based correlations), but very different configurations, necessarily have different actual manufacturing costs. For instance, let us consider two exchangers having the same heat transfer area but very different length to diameter ratio. This means we are comparing an exchanger having few long tubes with one having many shorter tubes. In the latter case the shell will have a much greater diameter and, for a given internal pressure, will have a greater thickness.

Moreover, the number of holes on the tube-sheets will be different as is the number of tubes to be mounted. Furthermore, exchangers designed according to standard methods tend to have a length-to-diameter ratio between 3 and 15, while specific design requirements or computerized design procedures can give rise to non standard configurations for which standard parametric correlations may not apply. Therefore, parametric cost functions should be limited to budget estimates instead of design applications, while analytical-generative methods should be used for design and optimization purposes.

Overall, analytical-generative cost estimating procedures are preferable for design purposes because:

- allow to estimate costs instead of prices and thus assess the impact of design choices on manufacturing cost irrespective of marketing strategies the firm may pursue;
- generate up to date costs without resorting to cost indices if current labor rates and material prices are given;
- may be easily updated to factor in changes in technologies and manufacturing processes;
- may easily factor in the actual costs incurred, which may vary according to the manufacturer even when the same production process is adopted (i.e one manufacturer may benefit from quantity discounts on materials, while another may suffer from higher wage rates), or may reflect variations in the manufacturing process utilized;
- estimate a cost which is consequent of the actual geometrical configuration of the equipment and is sensitive to changes in the detailed constructive features chosen by designers, thus allowing to discriminate between different configurations of equipment having the same overall size and compare design alternatives;
- avoid the limitations connected to the validity of parametric correlations over limited size ranges.

Therefore, in order to provide a cost estimation procedure having the required degree of detail to capture the actual exchanger architecture and its manufacturing process characteristics, as influenced by the chosen design parameters, an analytic-generative approach will be developed in the following section.

However, we would like to point out that the proposed analytical-generative method is not in competition with or an alternative to established parametric methods used to estimate purchase market price. This method is developed, instead, to estimate manufacturing cost mainly for design and bidding purposes. Estimates obtained through these two approaches can not be compared because are obtained from totally different perspectives (the manufacturer/designer vs the buyer) and for quite different purposes (equipment design vs purchase or capital cost estimation).

4. SHELL-AND-TUBE HEAT EXCHANGERS COST MODEL DEVELOPMENT

This model is referred to the AEL TEMA type heat exchanger, with one shell and tube pass and front and rear end channel type (Fig. 2). The bonnet end type is generally less expensive due to the reduced bolts number and welding length. Although each manufacturer can adopt specific construction procedures and proprietary equipment, a general process plan for manufacture of fixed tube-sheet exchangers has been given by Kuppan (Kuppan, 2000), and it has been assumed as a basis for the model developed in this work. Estimation relationships for process operations, instead, have been freely adapted from Creese and Adithan (1992).

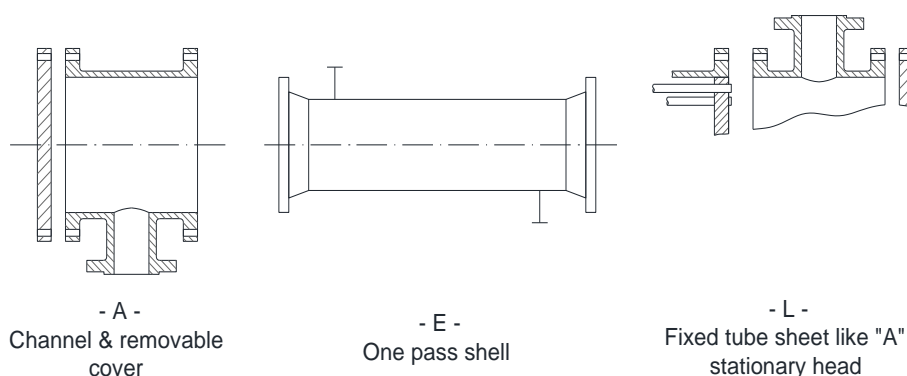


Fig. 2. Scheme of AEL TEMA type shell and tube heat exchanger.

The manufacturing cost of the heat exchanger (C_E) can be computed as the sum of the materials and processing cost (C_{m_x}) of its main subassemblies, listed in Table 1 along with their main processing operations.

$$C_E = \sum_x C_{m_x} \quad (8)$$

Table 1. Decomposition of a heat exchanger into its major sub-assemblies and their main processing operations.

(1)	Shell	Plate cutting
		Plate rolling
		Edge bevelling
		Plate welding
(2)	Tube-Sheet	Plate cutting
		Drilling
(3)	Tubes bundle	Tube cutting
		Welding
(4)	Baffles	Plate cutting
		Drilling
		Edge bevelling
(5)	Channel	Plate cutting
		Edge bevelling
		Plate rolling
		Welding
(6)	Flange	Plate cutting
		Drilling
(7)		Final Assembly

For sake of simplicity, cost models are developed for shell, tube-sheet, tubes bundle and baffles only, while Appendix III gives formulas for estimating the cost of components which do not significantly contribute to equipment cost (i.e. flanges and end plates or channels, tierods, spacers, bolts etc.). Other auxiliary and minor components (nozzles, impingement plate etc.) are neglected. Processing cost models are developed for main operations, while auxiliary ones, such as surface treatments (pickling, sandblasting, painting etc.) or welds quality control are neglected as well.

Each subassembly is manufactured resorting to traditional carpentry and machining operations, such as plate rolling, cutting, edge preparation (chamfering), welding, drilling and reaming. Estimation of operations cost and materials cost can be carried out in a parametric manner by knowing the set of main geometrical features of the heat exchanger as defined by thermal and structural designers, namely, length, diameter and thickness of shell, tubes, and channels; number of tubes; diameter and plate thickness of baffles; thickness and diameter of tube-sheets; thickness and diameter of shell flanges.

The cost of each subassembly, in turn, is defined as

$$C_{m_x} = C_{mat_x} + \sum_{k=1}^{N_{op}} C_{op_k} \quad (9)$$

where

$$C_{mat_x} = V_x \rho_x C_{mat,x} \quad (10)$$

is the x -th subassembly material cost estimated as the material volume V (m^3) times the material density ρ (kg/m^3) and its specific cost C_{mat} ($\text{€}/kg$), while

$$C_{op,k} = (L_k/v_k) C_{H,k} \quad (11)$$

is the cost of the k -th manufacturing operation required by the x -th subassembly, where L_k is the processing length (m), v_k the processing velocity (m/h) and $C_{H,k}$ the hourly cost of the manufacturing process (€/h), while N_{op} is the number of different process operations required by each subassembly. In greater detail the hourly cost of a processing operation is the sum of labor cost, equipment depreciation cost, energy cost and other consumables as

$$C_{H,k} = C_{H,L,k} + C_{H,E,k} + C_{H,O,k} \quad (12)$$

where the hourly depreciaton cost is

$$C_{H,E,k} = I_k \cdot \tau_k / h \quad (13)$$

being τ the capital recovery factor, I the capital investment of the processing equipment and h the number of yearly working hours. Hourly labor cost is

$$C_{H,L,k} = LR \cdot m \quad (14)$$

where LR is the labor rate (€/h) and m the number of workers participating to that processing operation. Finally, hourly energy and other consumables cost is

$$C_{H,O,k} = P_k \cdot C_{kWh} + C_{H,O,AUX,k} \quad (15)$$

being P (kW) the consumed power, C_{kWh} the electricity or energy cost (€/kWh) and $C_{H,O,AUX}$ the hourly cost of consumables and auxiliary materials. For reader convenience a nomenclature is added at the end of the paper.

Here, for sake of simplicity, the cost of manufacturing operations is expressed only considering the time duration of each operation without factoring in fixed costs or auxiliary operations. However, in Appendix III detailed formulas are given for a more precise estimation of manufacturing costs, including for instance equipment set-up.

In order to actually estimate equipment cost (i.e to estimate L_k and V_k values) the manufacturing process for each subassembly should be defined at first. Figure 3 depicts the manufacturing process for the shell.

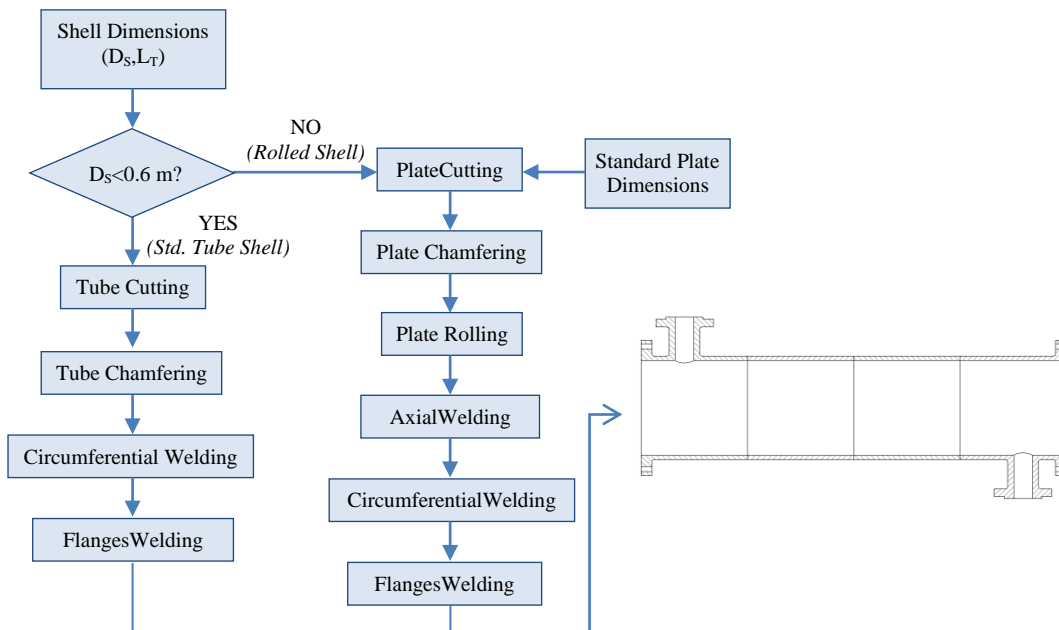


Figure 3. Scheme of shell manufacturing process.

The heat exchanger shell can be produced by different technologies depending on its size. Generally, up to internal diameter (D_S) of 600 mm a commercial seamless tube can be used, whereas for larger size the shell is made by welding rolled plates. The two options determine different production cycles and costs. The latter procedure is much more expensive. For sake of simplicity the flanges at the shell ends are assumed to be made starting from a plate. This is the usual practice for non overly stressed flanges. If thermal or load stresses are high the flanges are produced by casting processes and machining.

The baffles manufacturing process is depicted instead in Figure 4. Baffles are often of segmental type. They are made cutting to shape a square plate, beveling its edge and drilling a set of holes according to the tubes number and the pitch arrangement. Drilling is made bundling all the baffles one on top of the other and firmly holding them during the operation. This practice allows to drill in a single pass all the corresponding holes in line through the entire set of baffles, without any axial position error.

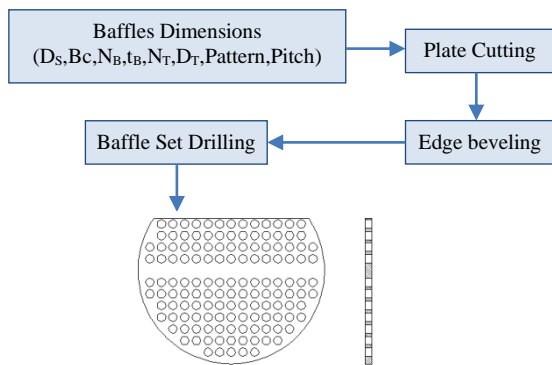


Figure 4. Scheme of baffle manufacturing process.

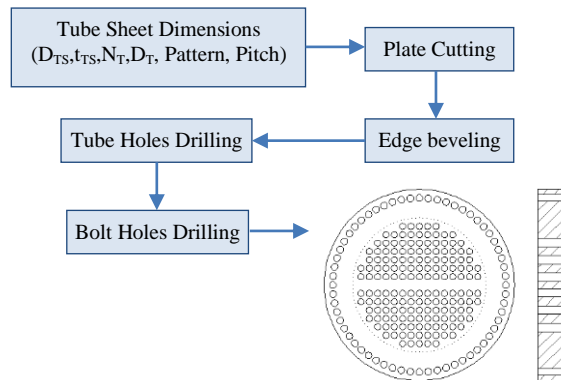


Figure 5. Scheme of Tube-sheet manufacturing process.

The tube-sheets in AEL heat exchangers are generally two. However, it is possible to have a double plate construction. In this work we compute the cost of each tube-sheet according to the process depicted in Figure 5. The tube-sheet construction needs particular attention and it is one of the major time consuming tasks. Frequently, the heat exchanger reliability is strongly dependent on the tube-tube-sheet junction, as it can cause leakage and corrosion attack. To allow a defect-free construction the tube-sheet must be drilled and reamed, assuring the adequate roughness.

For the TEMA type AEL the front and rear ends of the heat exchanger are channel type. As the channel has a construction procedure (Figure 6) very similar to the shell body (Figure 3), the same estimation procedure can be used, referring to the channel length L_{CH} instead of L_S . Furthermore, the channel type end is bolted at one end to the shell, and at the other end it requires a dished end bolted to its flange. The dished end cost is calculated factoring in material cost and labor cost for cutting, hole making and drilling a plate.

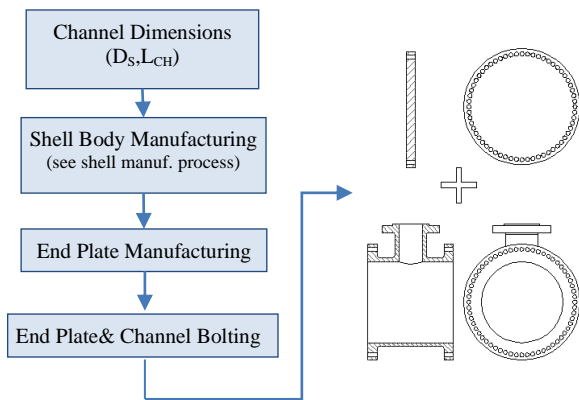


Figure 6. Scheme of tube-sheet manufacturing process.

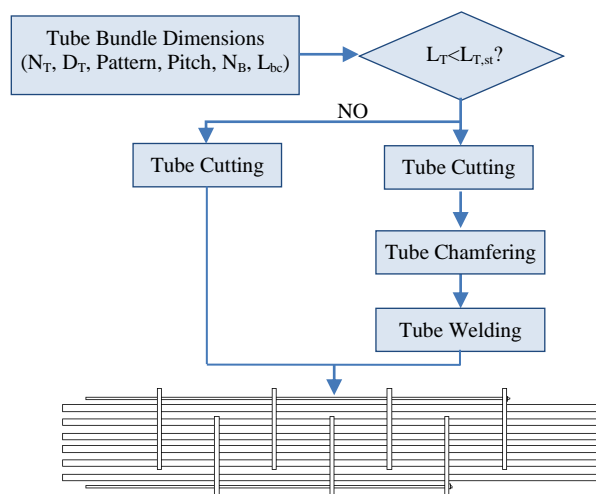


Figure 7. Scheme of tube bundle assembly process.

Passing to the tubes bundle fabrication (Figure 7), it is possible to assemble it outside of the shell body and then insert it into the shell, or to assemble the bundle directly inside the shell body. The latter option is more common, given the simplicity of handling lighter parts instead of the heavier tubes bundle subassembly. The assembly is a hand-made operation and the total time to insert the tubes into the rack of baffles and tie rods can be correlated to the time to insert the tube into one hole. After tubes have been set they are joined to tube-sheet during the final assembly stage, resorting to rolling-in process, an explosive joining or an hydraulic expansion. Afterwards, several reliability checks can be made on joints including pull-out or push-out procedures and leak tests.

The cost of handling subassemblies between workstations can be significant, but it is difficult to account as it depends on factory layout. However, it is possible to include the handling cost on a distance and weight basis. In this model this cost item is neglected. Instead, the handling cost to load and unload heavy parts on the workstation is explicitly included in the models of Appendix III.

From the above description it follows that manufacturing a shell and tubes heat exchanger implies the following set of main processes, namely, plates or tubes cutting and beveling, plates rolling, as well as plates drilling, and plates or tubes welding.

The described model is detailed enough to properly estimate the net manufacturing cost, based on main process operations and the main geometrical features determined by equipment designers. The method can be easily implemented in spreadsheet format or can be coded in numerical design optimization software in order to act as a quick decision support tool for designers, manufacturers and marketing people. In the following, parametric equations are used to estimate material volume and length of geometrical features involving processing operations, in order to estimate material cost and manufacturing cost as described in Equations 9, 10 and 11.

4.1 Material requirements computation

4.1.1 Shell

Assuming that the shell length is equal to that of the tubes bundle and that shell plates thickness can be determined according to Mariotte formula, the shell material volume is

$$V_{S,mat} = \pi \cdot D_{S,i} \cdot \frac{p_S \cdot D_{S,i}}{2 \cdot \sigma_S} \cdot L_T \quad (16)$$

where $D_{S,i}$ is the shell internal diameter, p_S the shell internal operating pressure, σ_S the allowable material stress and L_T the tubes (and shell) length.

In order to estimate exchanger length it is necessary to estimate the number of tubes N_T which can be housed inside a shell of given diameter D_s . This can be determined resorting to the following empirical equation

$$N_T = k1 \cdot \left(\frac{D_{bu}}{D_{T,o}} \right)^{n1} \quad (17)$$

where precise values for dimensionless constants $k1$ (in the range 0.21 to 0.03) and $n1$ (in the range 2.14 to 2.67) are available in design handbooks (Sinnott, 2005) as a function of the number of tube passes and type of tubes pitch. In Eq. (17) $D_{T,o}$ is the tubes outside diameter, while the diameter of tubes bundle (D_{bu}) is linked to shell internal diameter (D_s). A common design rule (Sinnott, 2005) is

$$D_{bu} = k2 \cdot D_{s,i} \quad (18)$$

where value of dimensionless constant $k2$ (Sinnott, 2005) depends from shell type and increases with increasing D_s . Obviously $k2 < 1$ as the shell must contain the tubes bundle.

Therefore, the shell and tubes length for a given heat transfer surface S , is

$$L_T = \frac{S}{\pi \cdot D_{T,o} \cdot N_T} = \frac{S}{\pi \cdot D_{T,o} \cdot k1 \cdot \left(\frac{k2 \cdot D_{S,i}}{D_{T,o}}\right)^{n1}} = \frac{S}{\pi \cdot D_{T,o}^{1-n1} \cdot k1 \cdot k2^{n1} \cdot D_{S,i}^{n1}} \quad (19)$$

By substituting Eq. (19) in Eq. (16) the overall shell material volume can be expressed as

$$V_{S,mat} = k3 \cdot \frac{D_{S,i}^{2-n1}}{k2^{n1}} \quad (20)$$

where constant $k3 = \frac{p_s \cdot S}{2 \cdot \sigma_s} \cdot \frac{1}{D_{T,o}^{1-n1} \cdot k1}$ can be computed when p_s , σ_s , pitch type, pitch ratio and tubes diameter have been selected by the designer.

In Eq. (20) denominator increases as D_s grows ($k2 < 1$ and $n1 > 2$) while numerator weakly grows when D_s increases (minimum value of the D_s exponent is 0.142 and maximum 0.643). Therefore, the overall effect is that shell material volume decreases when shell diameter grows because shell thickness increase is more than offset by the simultaneous shortening of shell length, for a given heat transfer area, resulting from the higher number of tubes housed within the shell.

4.1.2 Tube-sheets

As a rule of thumb, tube-sheet thickness is estimated as $0.1 D_s$ (and never less than 25 mm). Therefore, when shell diameter increases the tube-sheets material volume increases too owing to both the growth in plate diameter and its thickness. More precisely the tube-sheet thickness t_{TS} can be expressed as

$$t_{TS} = 0.5 \cdot D_{S,i} \cdot \sqrt{\frac{p_s}{\sigma_s}} \quad (21)$$

Usually tube-sheets have a diameter slightly larger than the diameter of the shell in order to be bolted to shell flanges and to channels Assuming that this excess diameter is a given percentage Dr of shell diameter (but not smaller than 50 mm computed along the diameter, i.e. for a 200 mm shell the tube-sheet diameter is at least $200+50+50 = 300$ mm), then the tube-sheets material volume is estimated as

$$V_{TS,mat} = \pi \cdot \frac{(D_{S,i} \cdot (1+2 \cdot Dr))^2}{4} \cdot t_{TS} \cdot N_{TS} \quad (22)$$

being N_{TS} the number of tube-sheets.

4.1.3 Tubes

Tubes thickness depends from the exchanger operating pressure. If the exchanger geometry changes, the internal pressure remains the same and tubes thickness does not change unless their diameter is changed by the designer. Nevertheless, when shell diameter increases the number of tubes making the bundle increases as well, and the exchanger length will decrease in order to maintain the same surface area. As a consequence, in general the tubes material volume is

$$V_{T,mat} = \pi \cdot \frac{D_{T,o}^2 - D_{T,i}^2}{4} \cdot L_T \cdot N_T \quad (23)$$

where $D_{T,i}$ is the tubes internal diameter. However, using Eq. (19) to determine L_T and Eq. (17) to compute N_T the following expression is obtained,

$$V_{T,mat} = \pi \cdot \frac{D_{T,o}^2 - (D_{T,o} - 2 \cdot t_T)^2}{4} \cdot \frac{S}{\pi \cdot D_{T,o}^{1-n1} \cdot k1 \cdot k2^{n1} \cdot D_{S,i}^{n1}} \cdot k1 \cdot \left(\frac{k2 \cdot D_{S,i}}{D_{T,o}}\right)^{n1} = (t_T \cdot D_{T,o} - t_T^2) \cdot \frac{S}{D_{T,o}} \quad (24)$$

being t_T the tubes wall thickness, showing that tube material volume is independent from D_s .

4.1.4 Baffles

Baffles are assumed to be of the segmental type. To estimate the material volume for a single baffle we consider the total baffle surface S_B (excluding the baffle window but including the material to be drilled to allow tubes passage)

$$S_B = \pi \cdot \frac{D_{S,i}^2}{4} \cdot \left(1 - \frac{1}{\pi} \cdot k4\right) + \frac{D_{S,i}^2}{2} \cdot \sin(k4) \cdot \left(\frac{1}{2} - Bc\right) \quad (25)$$

where Bc is the baffle cut and dimensionless constant $k4$ is computed as follows

$$k4 = \cos^{-1} \left(\frac{0.5 - Bc}{0.5} \right) \quad (26)$$

Once a baffles thickness (t_B) is defined, the overall baffle material volume is easily computed. Usually baffle thickness does not result from an explicit computation but is a matter of manufacturing practice and is unrelated to shell diameter. The computation of baffles number, instead, is functional to the required thermal and flow performances of the equipment. Therefore, it is strictly interconnected to thermal design to satisfy a specific duty. However, the practical central baffles distance L_{bc} is $0.2 D_s < L_{bc} < D_s$ (with lower bound of 50 mm), so that considering the average value we set

$$L_{bc} = \max \left(0.05; \frac{0.2 \cdot D_{S,i} + D_{S,i}}{2} \right) \quad (27)$$

and the conventional baffles number N_B (even non integer) results as

$$N_B = \frac{L_T}{L_{bc}} \quad (28)$$

leading to a total baffles material volume

$$\begin{aligned} V_{B,mat} &= S_B \cdot t_B \cdot N_B \\ &= D_{S,i}^2 \cdot \left[\pi \cdot \frac{1}{4} \cdot \left(1 - \frac{1}{\pi} \cdot k4\right) + \frac{1}{2} \cdot \sin(k4) \cdot \left(\frac{1}{2} - Bc\right) \right] \cdot t_B \cdot \frac{1}{0.6 \cdot D_{S,i}} \cdot \frac{S}{\pi \cdot D_{T,o}^{1-n1} \cdot k1 \cdot k2^{n1} \cdot D_{S,i}^{n1}} \\ &= k5 \cdot D_{S,i}^{1-n1} \end{aligned} \quad (29)$$

$$\text{being } k5 = \left[\pi \cdot \frac{1}{4} \cdot \left(1 - \frac{1}{\pi} \cdot k4\right) + \frac{1}{2} \cdot \sin(k4) \cdot \left(\frac{1}{2} - Bc\right) \right] \cdot t_B \cdot \frac{1}{0.6} \cdot \frac{S}{\pi \cdot D_{T,o}^{1-n1} \cdot k1 \cdot k2^{n1}}$$

In Eq.(29) the value of constant $k5$ is known when the overall characteristics of the exchanger are defined (Bc , pitch type, D_t , S). Considering that constant $n1 > 2$ it follows that baffles volume depends from D_s raised to a power in the range -1.142 to -1.675.

4.2 Manufacturing operations

4.2.1 Shell manufacturing

At first let us assume that the shell is made resorting to rectangular plates having length L_P and width W_P (in the following, subscript st may be added to identify standard commercial plates size). Then it is possible to compute the overall length to be cut in order to obtain a shell having a diameter D_s and length L_T . One or more plates are rolled and joined in order to make a circumferential trunk of the shell. Several of these trunks are then welded to make up the entire shell.

The number of rolled plates required to manufacture one circumferential trunk of the shell is (N_P)

$$N_P = \text{sup. int.} \left(\frac{\pi \cdot D_{S,i}}{L_{P,st}} \right) \quad (30)$$

and the total number of trunks to make the shell is (N_{RP}):

$$N_{RP} = \text{sup. int.} \left(\frac{L_T}{W_{P,st}} \right) \quad (31)$$

The overall length of axial and transversal cuts and chamfers $L_{P,c}$ or bevelings $L_{P,b}$ is

$$L_{P,c} = L_{P,b} = 2 \cdot L_T + 2 \cdot \pi \cdot D_{S,i} \cdot N_{RP} \quad (32)$$

The length $L_{P,w}$ of axial and transversal welds is

$$L_{P,w} = L_T + \pi \cdot D_{S,i} \cdot (N_{RP} + 1) \quad (33)$$

The total length $L_{P,r}$ of plates to be rolled is

$$L_{P,r} = \pi \cdot D_{S,i} \cdot N_{RP} \quad (34)$$

When the shell is obtained from a standard commercial pipe the sole manufacturing operation is cutting to a desired length, or head to head circumferential welding of two separate tube trunks in case the shell should be longer than the standard tube length.

4.2.2 Tube-sheets manufacturing

Tube-sheets need to be cut from a square or rectangular plate. Remembering that their thickness is t_{TS} and external diameter is $D_{S,i} \cdot (1 + 2 \cdot Dr)$ the overall cut length is

$$L_{TS,c} = \pi \cdot D_{S,i} \cdot (1 + 2 \cdot Dr) \quad (35)$$

As far as drilling is concerned one should consider both the holes for tubes passage and the holes required to bolt the tube-sheets to the shell. We assume that the latter set of holes are along a circumference with a diameter intermediate between the tube-sheet and the shell, with spacing bd . The resulting number of holes to be drilled is

$$N_h = N_T + \text{inf. int.} \left(\frac{\pi \cdot D_{S,i} \cdot (1 + Dr)}{bd} \right) \quad (36)$$

and the total drilling length

$$L_{TS,d} = N_h \cdot t_{TS} \cdot N_{TS} \quad (37)$$

4.2.3 Tubes processing

Process operations required for exchangers tubes are: cutting to length, in case the purchased tube is longer than required, or cutting and welding in case the exchanger is longer than a commercial tube so that more tubes need to be joined, and at least one cut to measure. It should be pointed out that suppliers make available tubes for heat exchanger applications up to 20 m long so that head-to-head welding may not be required.

The number of welds $N_{T,w}$ required for each tube is

$$N_{T,w} = \text{sup. int.} \left(\frac{L_T}{L_{T,st}} \right) - 1 \quad (38)$$

In case $N_{T,w} \neq 0$ the overall circumferential length $L_{T,w}$ is

$$L_{T,w} = N_{T,w} \cdot N_T \cdot \pi \cdot D_{T,o} \quad (39)$$

Tubes cutting is required any time that exchanger length is not an integer multiple of commercial tube length. In this case the overall circumferential cut length $L_{T,c}$ is

$$L_{T,c} = \begin{cases} \pi \cdot D_{T,o} \cdot N_T & \text{if } \frac{L_T}{L_{T,st}} \neq \text{int} \\ 0 & \text{otherwise} \end{cases} \quad (40)$$

It should be reminded that even if commercial exchanger tubes are long enough so that welding two or more tubes is a rare occurrence, the solution space to be explored by a computerized design procedure may include exchangers having uncommon lengths, thus requiring welds, which need to be nevertheless costed.

4.2.4 Baffles manufacturing

Each baffle needs cutting along its entire perimeter length and then needs to be drilled. The overall cut length is

$$L_{B,c} = D_{S,i} \cdot [(\pi - k4) + \sin(k4)] \cdot N_B \quad (41)$$

while the overall drilling length, assuming that tubes are uniformly distributed within the shell, is

$$L_{B,d} = \frac{N_T}{\pi \cdot \frac{D_{T,o}^2}{4}} \cdot S_B \cdot t_B \cdot N_B \quad (42)$$

If a more precise estimation is desired equations are available in exchangers design handbooks to compute the exact number of tubes crossing the baffles (i.e. requiring a hole) and those passing through the baffle window.

4.2.5 Flanges manufacturing

Each flange, having a thickness t_{FL} , needs cutting over an overall length

$$L_{FL,c} = 2 \cdot \pi \cdot D_{S,i} \cdot (1 + Dr) \quad (43)$$

while the total drilling length is

$$L_{FL,d} = \text{inf. int.} \left(\frac{\pi \cdot D_{S,i} \cdot (1 + Dr)}{bd} \right) \cdot t_{FL} \quad (44)$$

4.2.6 Tubes bundle assembly

The time required to assemble a tube bundle is assumed to be a sum of the time required to insert tubes through the baffles and tube-sheets holes (T_{in}), and the time required required for tubes rolling (T_e) i.e. the operation allowing to clamp tubes to tube-sheets holes.

$$T_a = T_{in} + T_e \quad (45)$$

Total insertion time is proportional to the time needed to insert the tube in a hole, the number of tubes and the number of holes

$$T_{in} = ST_{in} \cdot \left(N_T \cdot N_{TS} + \frac{N_T}{\pi \cdot \frac{D_{S,i}^2}{4}} \cdot S_B \cdot N_B \right) \quad (46)$$

where ST_{in} is the specific insertion time, while tubes rolling time is

$$T_e = ST_e \cdot N_T \cdot N_{TS} \quad (47)$$

being ST_e is the specific tube expansion time.

5. MODEL DISCUSSION

In the preceding Section a fairly detailed model allowing materials and processing cost estimation of shell and tube heat exchangers, based on equipment geometrical features, has been developed. Although the model seems to require many input data, actually the model utilizes only eight independent design variables: heat exchanger TEMA type, internal shell diameter (D_S), tube outside diameter (D_T), tubes total length (L_T , i.e. heat exchanger's length), pitch pattern and pitch ratio, baffle cut (B_c) and baffles spacing (L_{bc}); all these dimensions and characteristics are always known during shell and tube design phase. The above presented method is intended to provide an estimate of manufacturing cost of heat exchangers instead of purchase price. It has been developed to provide equipment designers and developers of numerical optimization methods a tool to correlate manufacturing cost to detailed geometrical features of the exchanger structure instead of just to the surface area. In this respect the method is not intended to provide the absolute value of the manufacturing cost, but rather to assess manufacturing cost in a relative manner, i.e. to assess how manufacturing cost is affected by changes in the geometrical features of the equipment. Therefore, this novel costing method is not intended as a substitute of, and can not be compared to, other available costing methods for heat exchangers. In fact, all available methods to estimate exchangers cost, including parametric correlations, are aimed at estimating purchase price instead of manufacturing cost. As a consequence, we are not claiming that parametric correlations (i.e. Hall's correlations) are uncorrect, because they are just fine to estimate purchase price. They are instead "uncorrect" to estimate manufacturing cost, and are conceptually unsuitable to be used in heat exchangers design optimization procedures. In Section 3 ample demonstration of this claim has been given.

In general an estimation method should be at first validated to demonstrate on an absolute basis that it correctly estimates the manufacturing cost of a heat exchanger before using it to compare two alternative solutions. However, a formal validation of the proposed cost estimation model is not included in this paper as it is not practicable owing to the following reasons.

- a) In the literature there is no comparable and validated manufacturing cost estimation model which can be used as a benchmark. Therefore, this model can not be validated against an alternative literature model.
- b) No publicly available heat exchangers manufacturing cost data are available to be compared with this model output. All published heat exchangers cost data refer to purchase price, as no manufacturer would disclose its true manufacturing cost. Nevertheless, owing to the presence of a mark-up on manufacturing cost to cover overheads and company profit, publicly available purchase price data are useless to validate a manufacturing cost model which does not include those additional cost items.
- c) Even if a manufacturer would declare its manufacturing cost for a given heat exchanger, this value would not be reliable enough to provide a validation for our model. In fact, a manufacturer would estimate its manufacturing cost resorting to some cost accounting procedure. However, such administrative methods are prone to data collection errors (i.e. error or ambiguity in recording of true number of work hours) data input errors (i.e. wrong definition of the true hourly cost of a resource) or can be simply applied in an improper manner. Therefore, there would be no guarantee that the declared cost is the true one. Most companies, in fact, admit that they have problems in determining the true manufacturing cost of their products, especially in make-to-order environments for one-of-a-kind equipment. In our personal experience we found that companies quote their selling price based only on a rough estimate on equipment cost, mostly based on overall weight, and the profit margin is so high that it can accommodate any error in manufacturing cost estimation. Moreover, the company cost accounting method would not record the true intrinsic manufacturing cost but rather the obtained manufacturing cost as affected by the resources operational inefficiency. This means that while we are trying to estimate the cost of a properly manufactured equipment, we could compare this cost with the cost of an equipment manufactured by a maybe improperly managed

process. In this case it would not be possible to discriminate between a model error and an extra cost caused by poor process efficiency affecting the reference cost.

d) Even if a reliable reference manufacturing cost is provided by a manufacturer, we would not be sure of the detailed process that was used by the manufacturer to produce the equipment. In case the equipment was fabricated adopting a process different from the one described by our model a discrepancy would be observed even if both the estimated cost and the experimentally determined one were correct.

Nevertheless the absence of a formal validation of the model does not impair the model credibility and is not strictly necessary as justified below.

a) As previously stated this model is not intended to provide an "absolute" estimate of a manufacturing cost, but rather a "relative" cost estimation, i.e. one which can show cost changes when geometrical features of the equipment are modified during the design process even if the overall heat transfer area remains the same. This is enough to choose between alternative equipment configurations which is the scope of the model. To this end a model is needed which is sensitive to changes in equipment internal geometry instead of a model which is only sensitive to overall surface area. This model explicitly details the role played by each geometric feature in determining the material and manufacturing cost. Therefore, when the proposed cost model is used to estimate the cost of two exchangers obtained from two different design procedures, even if the user may not be sure of the accuracy of the absolute value of cost, he may be sure of which equipment is cheaper. In fact, when an equipment configuration A is declared as cheaper than an alternative configuration B this happens because configuration A uses less materials (this can be verified by simple geometrical computations) and/or consumes less machining or workers hours owing to shorter lengths of its structural components to be processed. This is an objective geometric fact, independent from the method used to estimate cost, and insensitive to any uncertainty connected to the ignorance of overhead costs and mark-up percentage implied by parametric correlation of purchase price. Overall, to determine which exchanger is the best between two generic configurations A and B this model only refers to objective geometrical features. If a systematic error affects the model then it would affect both cost estimates without changing the result of the comparison.

b) This model is based on the analytical-generative cost estimating approach. In the literature all analytical-generative cost models are not supplemented with a validation because they are "self-validated", meaning that a check that the model is correct is implicit in verifying that its constitutive equations are correct, provided that this kind of model merely reproduces the single steps of the production process. In fact, according to the analytical-generative approach, the total cost simply consists in a sum of material cost items and processing cost items. Material cost items derive from quantification of volume and weight of each structural component. Any error would only derive from neglecting the presence of a structural component or from errors in computing its volume starting from its geometrical parameters. The correctness of this procedure can be easily verified on the basis of theoretical reasoning. Manufacturing cost items quantify the cost of each processing operation based on the time required to perform it. This, in turn, is determined on the basis of the processing velocity and the geometrical size of the part features to be processed (i.e. holes, edges etc.). Any error would only derive from neglecting some process operations, assuming the wrong process operation to manufacture a part, or in errors when computing the geometrical features of components being processed. We derived the sequence of processing operations from heat exchangers manufacturing processes described in the literature, while equations used for estimating cost of processing operations are taken from accepted and already validated literature sources. We provide easily verifiable equations to compute the dimensions of geometrical features of components to be processed. Furthermore, we show that processing cost is only a minor part of the entire manufacturing cost. Therefore, any error in processing cost estimation is likely to have a negligible impact on the overall cost estimation, while material costs can be assessed on the basis of simple geometrical computations only, which are objective.

In conclusion, simple inspection of the self-explanatory equations included in the model provides an informal model validation that any interested reader can carry out. Moreover, the structure of the model is modular, so that the reader can change the model to suit its own manufacturing processes and use its own specific values of process or economical parameters (i.e. labour cost or machine hourly cost) in the model equations.

For the above cited reasons, although it is impracticable to experimentally validate this cost estimation model, it can instead be easily justified from a conceptual point of view by ensuring that all cost items are correctly and explicitly accounted for. This makes a formal numerical validation not strictly necessary. However, this only applies if the equipment is manufactured using the process described by the model.

6. SENSISTIVITY ANALYSIS

The developed model is used at first to explore how the equipment configuration can affect the overall equipment manufacturing cost, given a prescribed heat transfer area. As parameters of this sensitivity analysis we adopt the main design variables, i.e. tubes length, L_T , shell diameter D_S and tubes diameter D_T . In particular the aspect ratio L_T/D_S is the main indicator able to describe the overall configuration of a shell and tube heat exchanger. Traditionally, commercial exchangers tend to have L_T/D_S comprised within the values of 3 and 15, while the literature suggest to design "slender" (i.e. high aspect ratio) exchangers instead of "fat" ones to reduce costs (Purohit, 1982; Hewitt, 2008). Nevertheless, no justification for this statement is provided, while available parametric cost estimating correlation do not take into account at all this ratio. Here we demonstrate that L_T/D_S aspect ratio is really influential on equipment cost.

The previously developed model shows that when the shell diameter increases, at constant heat transfer area, the material volume

- decreases for the shell and baffles,
- is constant for tubes,
- increases for tube-sheets.

Therefore, an optimal shell diameter may exist which minimizes the overall material volume and weight, as shown in Figure 8 referring to a 200 m² exchanger.

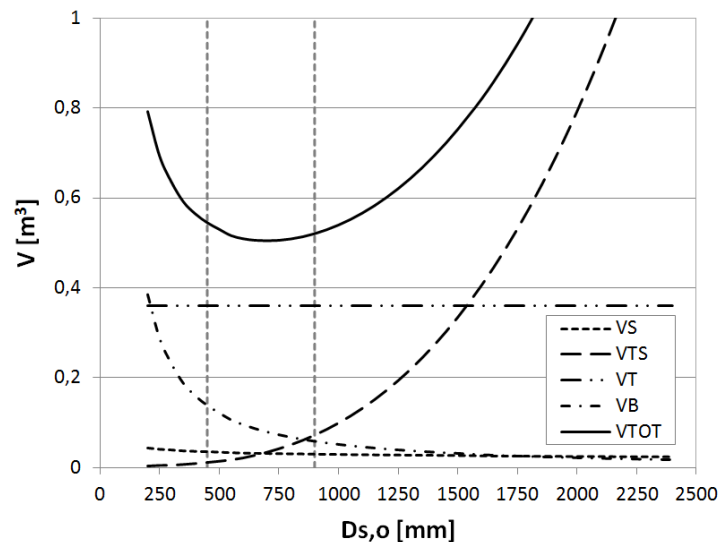


Figure 8. Material volume of main heat exchanger sub-assemblies when shell diameter changes (SRFH type, triangular pattern, 2 tube pass, $D_T = 20$ mm, $t_T = 2$ mm, $S = 200$ m², $B_c = 25\%$, $t_B = 20$ mm, $\sigma_S = 130$ MPa, $p_S = 10$ bar)

In Figure 8 the two dashed vertical lines represent the upper and lower boundary of suggested aspect ratio ($3 < L_T/D_S < 15$), i.e. the range of traditional aspect ratio. Using the parameters values indicated in Table 2, the processing, materials and total manufacturing cost can be computed as well, for the same exchanger of Figure 8, as shown in Figure 9.

Table 2. Values of parameters used in the sensitivity analysis.

$C_{mat,S}$	2	[€/kg]	$C_{H,c}$	62	[€/h]	v_c and $v_{c,T}$	1	[m/min]
$C_{mat,TS}$	3	[€/kg]	$C_{H,b}$	27.1	[€/h]	v_b	3	[m/min]
$C_{mat,T}$	2.4	[€/kg]	$C_{H,w}$	47.9	[€/h]	v_w	0.2	[m/min]
$C_{mat,B}$	1.5	[€/kg]	$C_{H,T,c}$	62	[€/h]	v_r	0.2	[m/min]
$C_{H,r}$	49	[€/h]	$C_{H,d}$	31.7	[€/h]	v_d	0.3	[m/min]

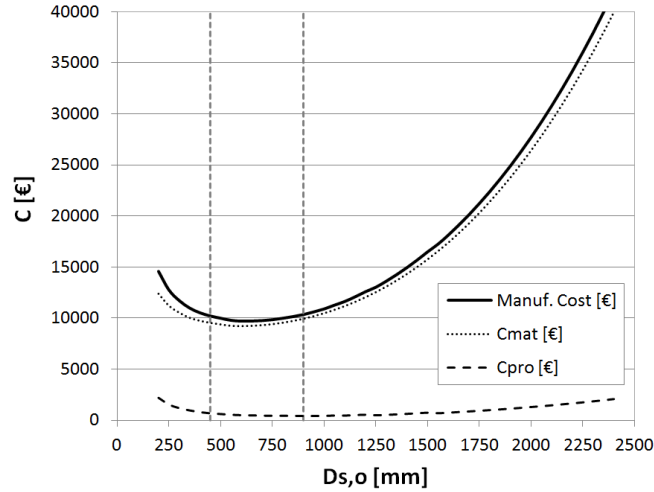


Figure 9. Materials, processing and total cost of 200 m² heat exchanger when shell diameter changes.

The following set of figures, 10a to 10f, show the total exchanger manufacturing cost when the transfer area changes from 100 m² to 600 m². It can be noticed that the minimum cost always falls within the suggested aspect ratio range ($3 < L_T/D_S < 15$) and that within this range the cost is nearly constant (cost variation within 6% to 8% passing from minimum to maximum cost within the considered aspect ratio range). This somewhat justifies the manufacturing practice and also justifies the resort to simplified parametric costing correlations as long as the exchanger falls within the default aspect ratio range, as often happens with commercial exchangers. Nevertheless, when an exchanger is designed for a different aspect ratio, the cost changes in a strongly non linear manner, so that the notion, derived from commonplace parametric correlation, that cost only depends from surface area and not from the equipment overall architecture is not justified from a general point of view.

The model also shows that the percent cost variation within the suggested ($3 < L_T/D_S < 15$) range increases when the overall surface area increases. Considered that parametric costing correlations are limited to smaller area heat exchanger then the hypothesis of constant cost for a given exchanger area can be assumed as reasonable for preliminary capital cost estimating purposes, although not for design purposes.

A further analysis has been made to investigate the impact that tubes diameter has on total manufacturing cost. Figure 11 refers to a 300 m² heat transfer area exchanger, and confirms that even tubes diameter is a variable which is likely to affect significantly the equipment cost for a given heat transfer area. This is an important result as tubes diameter is seldom included in parametric cost correlations and will strongly affect even the cost of exchangers designed within the traditional aspect ratio range.

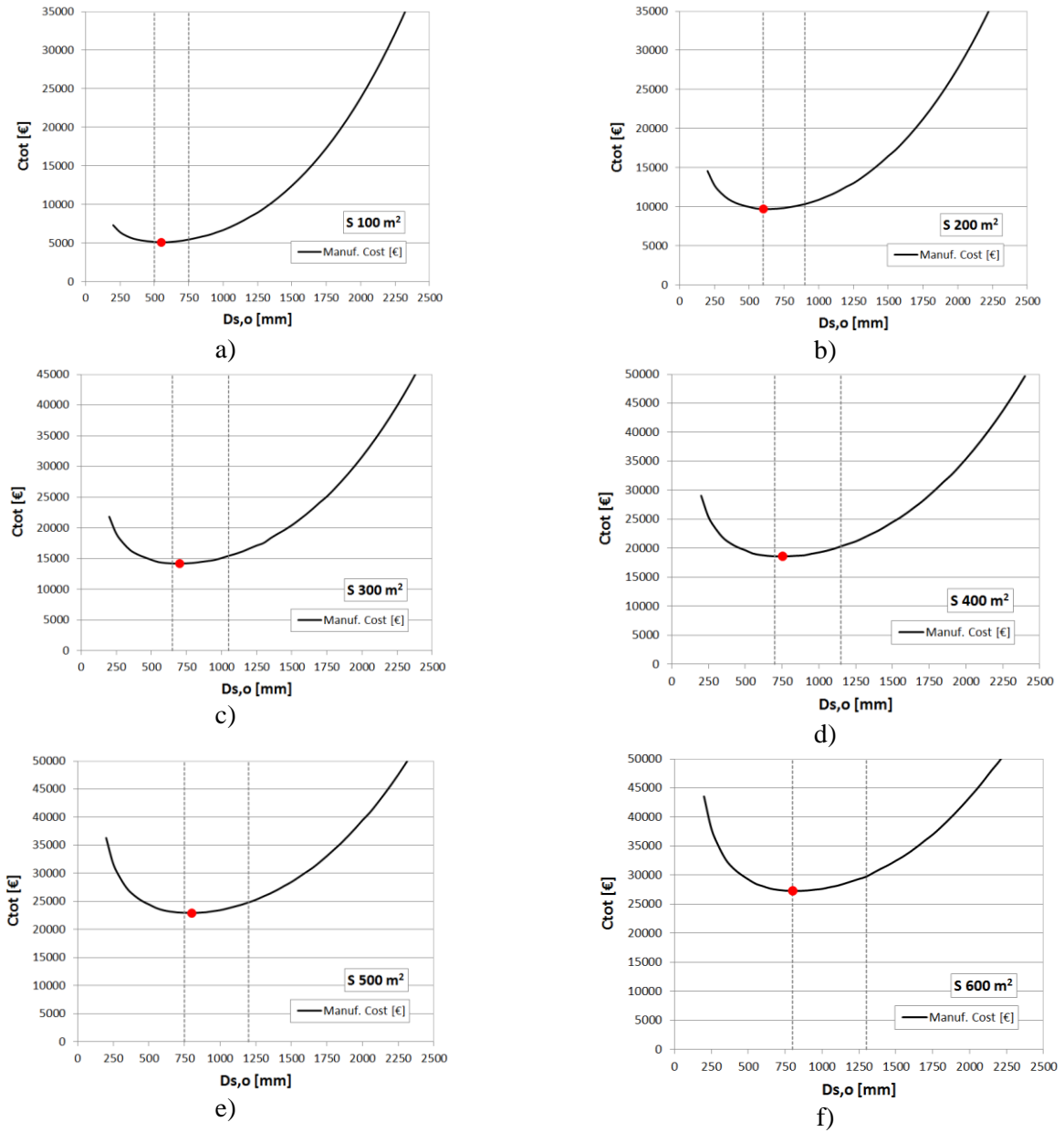


Figure 10. Total manufacturing cost when shell diameter changes for exchangers of different heat transfer area (dot indicated minimum cost diameter, while vertical dashed lines the $(3 < L_T/D_s < 15)$ range.

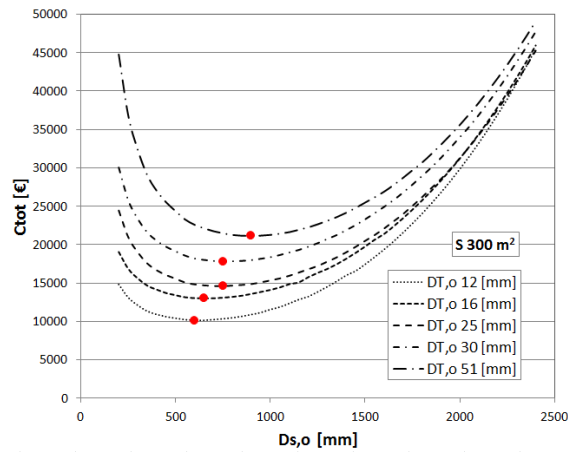


Figure 11. Total manufacturing cost when tubes diameter changes for a 300 m² exchangers.

7. NUMERICAL EXAMPLE

In this section a numerical heat exchanger optimization routine based on a genetic algorithm (Caputo et al., 2008) and using the Bell-Delaware sizing approach (Hewitt, 1998) is used for designing the equipment which minimizes an objective function representing the total life cycle cost of the equipment, sum of capital investment and discounted sum of pumping energy costs to overcome friction losses. The algorithm is run twice. One time when the objective function includes a traditional Hall parametric correlation

$$C_E (\$) = 30800 + 750 S^{0.81} \quad (48)$$

to estimate the capital investment. This equation is valid for exchangers made with carbon steel for both shell and tubes (Hall et al., 1990), updated with CEPCI index and converted to Euros. The second time when the objective function bases capital cost estimation on the manufacturing cost estimation method developed in this work. To ensure that both design can be consistently compared, given that in both cases the computerized procedures defines in great details all geometrical features of the equipment, the manufacturing cost of the optimal architecture obtained resorting to the objective function including the Hall correlation has been then costed according to the method developed in this work. This ensures that only manufacturing costs are accounted for and that the two equipment, although obtained resorting to different economic objective functions are costed using the same method.

Specifications for the test exchanger are taken from a literature case study (Sinnott 2005, 3rd ed., p. 675) and shown in Table 3. Required duty is 4340.7 kW and LMDT is 30.79 °C. A fixed tube-sheets heat exchanger, a 5 year operating period and an energy cost of 0.12 €/kWh are considered.

Table 3. Heat exchanger design specifications.

		Hot Fluid <i>Cond. Methanol</i>	Cold Fluid <i>Brackish water</i>
Inlet temperature	[°C]	95	25
Outlet temperature	[°C]	40	40
Mass flow rate	[kg/s]	27.78	68.90
Fluid density	[kg/m ³]	750	995
Thermal conductivity	[W/m K]	0.19	0.59
Fluid specificheat	[J/kg K]	2840	4200
Fluid viscosity	[mPa/s]	0.34	0.80
Fouling Resistance	[m ² K/W]	0.0002	0.00033

Values of constants and parameters used to perform computations are shown in Table 4.

Table 4. Parameters value

$C_{AUX,b}$	[€/su]	0	I_c	[€]	120,000	P_r	[kW]	100
$C_{AUX,c}$	[€/su]	0	I_{cw}	[€]	30,000	P_r	[kW]	100
$C_{AUX,cw}$	[€/su]	5	I_d	[€]	50,000	ST_e	[s/tube]	15
$C_{AUX,d}$	[€/su]	1	I_e	[€]	5,000	$ST_{in,br}$	[s/bolt]	30
$C_{AUX,r}$	[€/su]	0	I_r	[€]	100,000	$ST_{in,sp}$	[s/spacer]	15
$C_{AUX,w}$	[€/su]	10	I_w	[€]	75,000	$ST_{in,T}$	[s/tube]	3
C_{gr}	[€/m ²]	2	L_l	[mm]	3	$ST_{in,td}$	[s/tierod]	3
$C_{H,O,b}$	[€/h]	0.3	L_{ot}	[mm]	5	$T_{LU,b}$	[s]	30
$C_{H,O,c}$	[€/h]	10	$L_{P,st}$	[m]	6	$T_{LU,c}$	[s]	40
$C_{H,O,cw}$	[€/h]	5	L_{pt}	[mm]	5	$T_{LU,cw}$	[s]	180
$C_{H,O,d}$	[€/h]	1	LR	[€/h]	22	$T_{LU,d,B}$	[s]	240
$C_{H,O,e}$	[€/h]	0	m_b	[-]	1	$T_{LU,d,TS}$	[s]	120
$C_{H,O,r}$	[€/h]	0	m_c	[-]	1	$T_{LU,r}$	[s]	120
$C_{H,O,r}$	[€/h]	0	m_{cw}	[-]	1	$T_{LU,w}$	[s]	300
$C_{mat,B}$	[€/kg]	2	m_d	[-]	1	$T_{SU,b}$	[min]	10
$C_{mat,br}$	[€/kg]	2.5	m_e	[-]	1	$T_{SU,c}$	[min]	15
$C_{mat,FL}$	[€/kg]	2	m_r	[-]	1	$T_{SU,cw}$	[min]	5
$C_{mat,S}$	[€/kg]	2	m_w	[-]	1	$T_{SU,d,B}$	[min]	1

$C_{mat,sp}$	[€/kg]	2	Nyr_b	[yr]	5	$T_{SU,d,TS}$	[min]	1
$C_{mat,T}$	[€/kg]	3	Nyr_c	[yr]	5	$T_{SU,r}$	[min]	10
$C_{mat,td}$	[€/kg]	2	Nyr_{cw}	[yr]	10	$T_{SU,w}$	[min]	25
$C_{mat,TS}$	[€/kg]	3.5	Nyr_d	[yr]	5	v_b	[m/min]	1.5
C_{pa}	[€/m ²]	4	Nyr_e	[yr]	5	v_{cw}	[mm/s]	1.5
C_{pk}	[€/m ²]	5	Nyr_r	[yr]	5	v_r	[m/min]	0.33
C_{sb}	[€/m ²]	3	Nyr_w	[yr]	5	v_w	[m/min]	7
EC	[€/kg]	1.2	OF	[-]	0.5	WC	[A]	150
EMY	[-]	0.97	P_b	[kW]	15	WE	[-]	0.9
EWL	[kg/m]	0.0053	P_c	[kW]	100	WFR	[m/min]	2.5
GC	[€/m]	15	P_{cw}	[kW]	10	$W_{P,st}$	[m]	1.5
GFR	[m ³ /h]	1.4	P_d	[kW]	10	W_{pk}	[cm]	5
I_b	[€]	20,000	P_e	[kW]	5	WV	[V]	20

Table 5 shows the optimization results comparing the two optimized design in terms of geometrical features and economic performances (i.e. manufacturing cost, operating cost and total life cycle cost). Data in column labeled "This work" refer to the optimal exchanger obtained when the costing method discussed in this work is included in the objective function to compute the manufacturing cost intended as a proxy for capital investment. Data in column labeled "Hall (I)" refer to an optimal exchanger obtained when Eq. (48) by Hall is used to estimate capital investment in the objective function. Finally, column labeled "Hall (II)", shows instead an alternative configuration found by the optimization routine still using Eq. (48) to estimate capital investment. The fact the the same optimization routine can deliver different "optimized" equipment configuration is characteristic of heuristic stochastic optimization procedures such as genetic algorithms. Please note that while in Section 3 we stated that Hall's correlation are valid for area's below 140 m², here a Hall's correlation is used to cost an equipment having an heat exchange area above 200 m². The apparent contradiction can be explained by noticing that equations referred to in Section 3 are derived from Hall et al. (1982) who state the above cited size limit. However, Equation (48) is taken from Hall et al. (1990) for which in the original paper no mention is made to a size limit. This is another example of the ambiguity often surrounding parametric cost equations.

Table 5 clearly shows that, obviously, the optimized design procedure converges to two radically different equipment configurations when a change is made in the way the capital or manufacturing cost is estimated in the objective function. Nevertheless, for the given thermal duty, the configuration obtained with the detailed costing method is cheaper, in both the manufacturing cost and total cost, than the one obtained with the traditional costing method, when the obtained configurations are costed using the same detailed method. However, the reader may object that we compare equipment designed to minimize the life cycle cost but including in one case the manufacturing cost and in the other case the purchase price. This discrepancy is not relevant as we are simply comparing equipment resulting from two alternative design procedures but both aimed at the same ultimate objective. Then, the reader may object that in the above example we use two different costing procedures but do not prove which one is the correct one. At first it should be reminded that the different exchangers configuration obtained using two different objective functions, one estimating the manufacturing cost resorting to the analytical-generative approach and the other estimating the purchase price according to a statistical correlation, are always costed according to the same cost estimating method. In this manner we ensure that cost comparison of the alternative configuration is made in a consistent manner and that a relative cost comparison is carried out. However, formally we can not assess which of the costing method provides the "correct" estimate in absolute terms, given that the two methods estimate different quantities (i.e. a manufacturing cost and a purchase price) and can not be directly compared. Nevertheless, we show that the equipment designed with the analytical-generative objective function has a lower manufacturing cost, respect an exchanger designed using an objective function relying on parametric correlation for the capital investment, simply because it uses less materials and/or consumes less machining or workers hours owing to shorter lengths of its structural components to be processed. This objective geometrical evidence, together with the conceptual unsuitability of parametric correlations for detailed design optimization, determines that the equipment configuration obtained in this work is superior, from a cost perspective, to the one obtained using parametric cost correlations, irrespective of the absolute value of cost provided by parametric correlations, and independently from the circumstance that the compared exchangers may have a greater or lower overall heat exchange area, given that the same surface area could be obtained with different equipment configurations implying different amounts of processing hours or materials amount.

In fact, it is interesting to note that even if the exchanger designed using Hall cost function has a slightly smaller surface area, its manufacturing cost is higher than the one designed according to this work.

It is also interesting to note that in the case of "Hall (II)" exchanger the obtained configuration has a L_T/D_S ratio about 19, thus outside the traditional design range for which parametric correlations are built. Therefore, Eq. (48) utilized to find this solution might not be valid for the obtained solution! Nevertheless, this latter solution is economically worse than the preceding ones. However, while it is true that a constraint on L_T/D_S value may be coded in the optimization algorithm, it is not advisable to do so because this would limit the solution space preventing the algorithm to find convenient but "untraditional" architectures.

Table 5. Optimization results

Parameter			This Work	Hall(I)	Hall (II)
Shell diameter	D_s	[mm]	762.0	812.8	762.0
Shell thickness	t_s	[mm]	11.0	12.0	11.0
Bundle diameter	D_{bu}	[mm]	744.8	795.4	744.9
Baffle cut	B_c	[%]	40	27	31
Number of baffles	N_B	[-]	9	7	25
Central baffle spacing	L_{bc}	[mm]	700.0	357.0	537.0
Extremal baffles spacing	L_{bi}, L_{bo}	[mm]	700.0	429.0	556.0
Pitch ratio	$L_{tpRatio}$	[%]	1.30	1.39	1.29
Tubes ext. diameter	D_T	[mm]	20.0	10.0	44.5
Tubes int. diameter	$D_{T,i}$	[mm]	16.0	7.0	39.5
Tubes pitch	L_{tp}	[mm]	26.0	13.9	57.4
Tube layout angle	θ_{tp}	[deg]	90	90	30
Tube passes	N_{tp}	[-]	4	4	6
Temperature Correction Fact.	F_t	[-]	0.81	0.81	0.81
Tubes number	N_T	[-]	546	2262	116
Tubes length	L_T	[m]	7.2	3.2	14.2
Tubes net length	L_T	[m]	7.0	3.0	14.0
Length-Diameter Ratio	L_T/D_S	[-]	9.4	3.9	18.6
Tube Side	-	[-]	Hot fluid	Hot fluid	Hot fluid
Flow velocity (tube-side)	v_T	[m/s]	1.35	1.70	1.56
Flow velocity (shell-side)	v_S	[m/s]	0.54	0.82	0.74
Reynolds number (shell-side)	Re_S	[-]	13,342.8	10,147.5	40,877.9
Prandtl number (shell-side)	Pr_S	[-]	5.69	5.69	5.69
Reynolds number (tube-side)	Re_T	[-]	47,633.3	26,280.4	13,6225.9
Prandtl number (tube-side)	Pr_T	[-]	5.08	5.08	5.08
Convective heat transfer coefficient (shell-side)	α_S	[W/m ² K]	3484.2	5835.4	3462.4
Convective heat transfer coefficient (tube-side)	α_T	[W/m ² K]	3369.6	4636.7	3479.7
Overall heat transfer coeff.	U_{dirt}	[W/m ² K]	805.6	910.3	853.8
Heat exchange area	S	[m ²]	240.1	213.2	227.0
Pressure drop (shell-side)	Δp_S	[kPa]	9.71	23.03	27.43
Pressure drop (tube-side)	Δp_T	[kPa]	39.55	70.84	55.60
Operating cost present value	$C_{O,tot}$	[€]	6805.93	13,432.82	12,607.05
Manufacturing cost (this model)	C_E	[€]	22,641.45	27,573.45	28,259.34
Total life cycle cost (this model)	$C_E + C_{O,tot}$	[€]	29,447.38	41,006.27	40,866.39

Capital investment comparison, in terms of manufactured equipment cost, is summarized in Figure 12 for the tree examined exchangers, showing how the equipment designed using the detailed costing method is about 18% cheaper to manufacture. It also has a much lower life cycle cost thanks to the lower value of pressure losses. It is interesting to note that "This work" exchanger is credited with a lower manufacturing cost even if it has a higher heat transfer area (and hence a higher purchase price according to the adopted parametric costing correlation) because it consumes less materials or processing times. This confirms the unsuitability of parametric correlations for detailed equipment costing.

This numerical example is computed including all equipment components as well as auxiliary process operations (i.e. pickling, sandblasting, painting etc.) as described in Section 4 and Appendix III. Auxiliary operations represented 8.3% of processing cost and 1.9% of total manufacturing cost in the example considered. As far as auxiliary and minor components (tierods, spacers etc.) are concerned, their cost has been included too and their percent relevance has been shown in the cost breakdown figures included below. In case the total manufacturing cost is computed including only the main components referred to in Section 4, an overall cost about 17% lower would be obtained, confirming that flanges and channels represent a minor contribution.

Figure 13, shows the subdivision of manufacturing cost in processing cost and materials cost for the exchanger designed according to the proposed costing method. It can be observed that material cost accounts for a much higher percentage than processing cost. This confirms industrial practice.

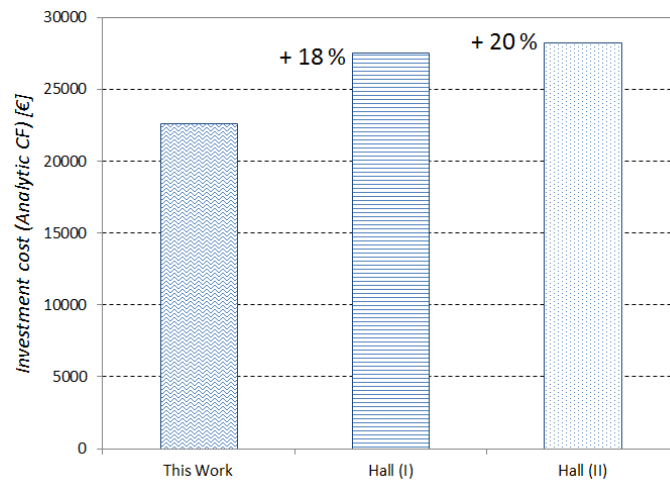


Figure 12. Comparison of total manufacturing costs.

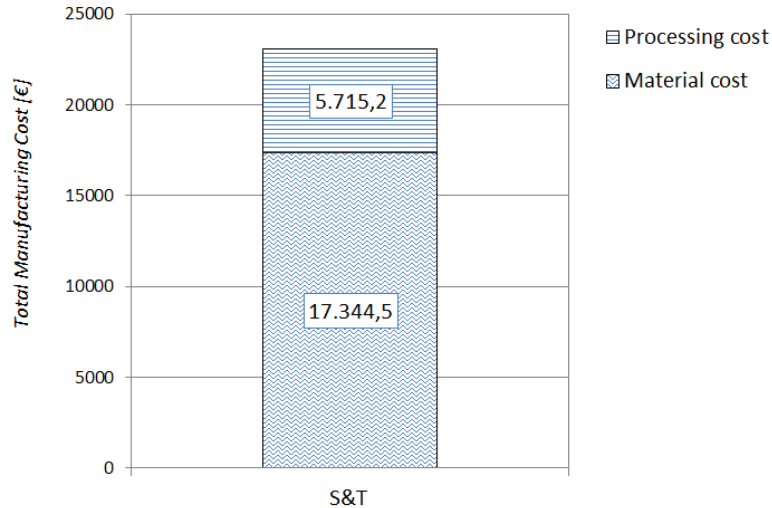


Figure 13. Breakdown of total manufacturing costs.

Figures 14 and 15 show respectively the percent allocation of materials and processing cost to the various sub-assemblies making up the heat exchanger. It can be observed that tubes bundle is by far the highest contributor to materials cost while shell cost, the second contributor, has a cost nearly double respect tube-sheets. As fa as processing costs are concerned, instead, baffles cost is the largest contributor with a cost nearly double respect tube-sheets. Processing cost of other components is roughly similar, with the shell being the more costly to manufacture.

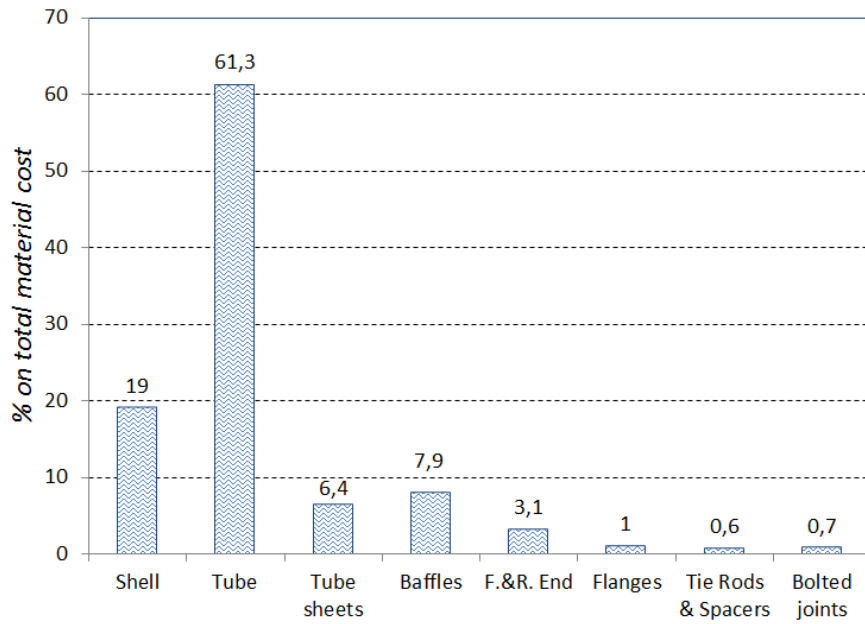


Figure 14. Percent subdivision of material cost among exchanger main components.

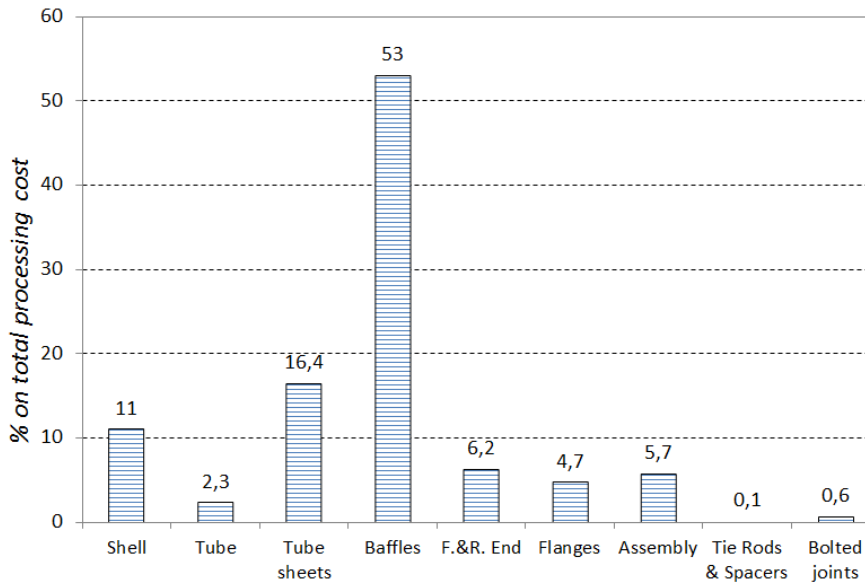


Figure 15. Percent subdivision of processing cost among exchanger main components.

Finally, Figure 16 shows the allocation of total cost (processing + materials) among subassemblies, which is quite similar to the materials cost breakdown, exception made for baffles, owing to the higher absolute value of materials cost respect processing costs. The above results also show how critical it is to correctly define the detailed equipment geometrical architecture, given a heat transfer area, if materials cost and processing cost are to be minimized, and that to find the equipment architecture with minimal surface area is not enough to define a minimum cost exchanger.

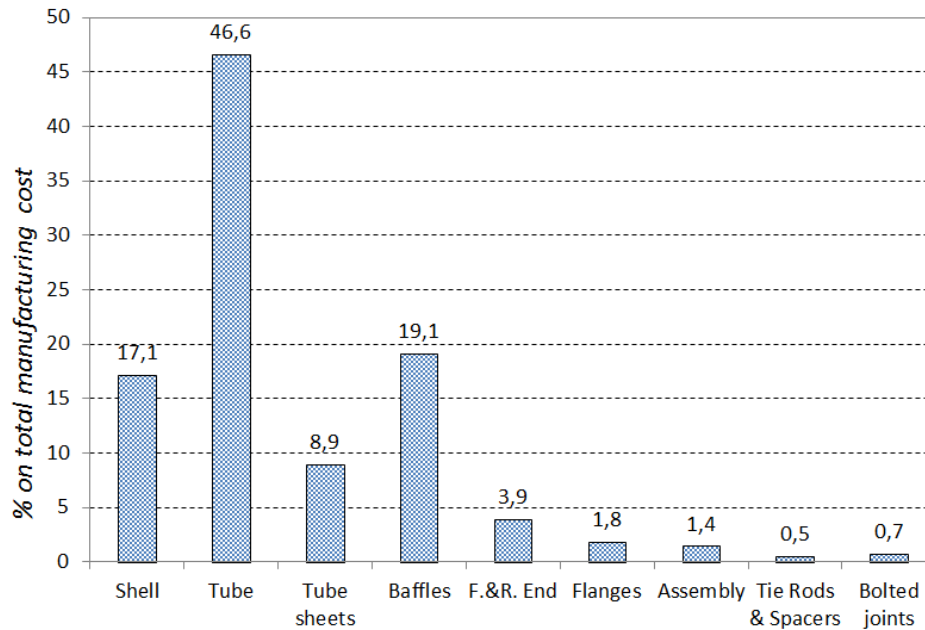


Figure 16. Percent subdivision of total manufacturing cost among exchanger main components.

8. CONCLUSIONS

In this work a fairly easy to use, but detailed manufacturing cost estimation method for shell and tube heat exchangers has been presented. It is based on a analytic-generative approach and can be used to accurately estimate the manufacturing cost of the equipment according to its detailed geometry and the utilized manufacturing resources and processes. Therefore, it can be used as a more precise alternative to traditional costing methods based on statistical correlations of purchase price, when a detailed estimate is needed to compare alternative equipment design or when the equipment cost is to be estimated in the framework of a design optimization procedure, which requires the cost function to be sensitive to all geometrical features of the exchanger instead of to the surface area only. Use of the model demonstrated how to use parametric correlation based on surface area, when computing objective functions in optimal design routines for heat exchangers, as currently made in the literature, is totally wrong either from the conceptual and practical point of views. The developed model also demonstrates that minimum cost designs most often satisfy a well defined aspect ratio range ($3 < L_T/D_S < 15$), thus analytically confirming a well known empirical rule of thumb. Nevertheless, the model also demonstrated that equipment cost is strongly sensitive to L_T/D_S ratio, even if this is not the unique geometrical parameter able to define the optimal equipment arrangement. This confirms that only a detailed costing method, together with advanced optimization tool able to effectively explore a multidimensional search space, allows designers to find an optimal equipment configuration, while to use numerical optimization method paired with simplified cost correlation leads to suboptimal solutions.

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NOMENCLATURE

Bc	[%]	Baffle cut
bd	[m]	Circumferential bolt distance
BS	[-]	Batch size
C	[€]	Cost
C_{kWh}	[€/kWh]	Power cost
Cm	[€]	Total manufacturing cost
$Cmat$	[€]	Material cost
D	[m]	Diameter
Dr	[%]	Diametral rise
EC	[€/kg]	Electrode cost
EMY	[-]	Deposition efficiency ratio
EWL	[kg/m]	Electrode weight per unit length
FC	[€/kg]	Flux cost
FCR	[kg _{flux} /kg _{metal}]	Flux consumption rate
Ft	[-]	Temperature correction factor
GC	[€/m ³]	Gas cost
GFR	[m ³ /h]	Gas flow rate
H	[m]	Height
I	[€]	Investment cost
$k1$	[-]	Numerical constant
$k2$	[-]	Numerical constant
$k3$	[-]	Numerical constant
$k4$	[-]	Numerical constant
$k5$	[-]	Numerical constant
L	[m]	Length or spacing
LR	[€/h]	Labour rate
m	[-]	Workers number
N	[-]	Number
$n1$	[-]	Numerical constant
Nyr	[yr]	Amortization time span
p	[MPa]	Pressure
P	[kW]	Equipment power
Pr	[-]	Prandtl number
Re	[-]	Reynolds number
S	[m ²]	Surface
ST	[h/item]	Specific time
t	[m]	Thickness
T	[h]	Time
U	[W/m ² K]	Overall heat transfer coefficient
V	[m ³]	Volume
v	[m/s]	Velocity
W	[mm]	Width
WC	[A]	Welding current
WE	[-]	Welder electric efficiency
WFR	[m/h]	Wire feed rate
WMD	[kg/m]	Weld metal deposited
WV	[kV]	Welding voltage
v	[m/s]	Velocity

Subscripts

a	assembling
AUX	auxiliary cost
B	baffle
b	bevelling
bc	baffle central
bt	bolt
bu	bundle

<i>c</i>	cutting
<i>CH</i>	channel end
<i>cw</i>	welding check
<i>d</i>	drilling
<i>E</i>	equipment
<i>e</i>	expansion (tube expansion)
<i>FL</i>	flange
<i>gr</i>	grinding
<i>H</i>	hourly (cost)
<i>h</i>	holes
<i>i</i>	inside
<i>in</i>	insertion (tube insertion)
<i>j</i>	item index
<i>k</i>	operation index
<i>L</i>	labor
<i>l</i>	lead
<i>LU</i>	load/unload
<i>mat</i>	material
<i>o</i>	outside
<i>O</i>	operating
<i>op</i>	operation
<i>ot</i>	overtravel
<i>P</i>	plate
<i>pa</i>	painting
<i>pk</i>	pickling
<i>pro</i>	processing
<i>pt</i>	pretravel
<i>r</i>	rolling
<i>RC</i>	removable cover
<i>RP</i>	rolled plate
<i>S</i>	shell
<i>sb</i>	sandblasting
<i>sp</i>	spacer
<i>st</i>	standard
<i>SU</i>	setup
<i>T</i>	tube
<i>td</i>	tie rod
<i>tp</i>	tube pitch
<i>tr</i>	trunk
<i>TS</i>	tube sheet
<i>w</i>	welding
<i>x</i>	subassembly index

Symbols

ρ	$[kg/m^3]$	Material density
σ	$[MPa]$	Allowable material stress
τ	$[%/yr]$	Capital recovery factor
ω	$[rpm]$	Drill spindle revolutions per minute
α	$[W/m^2 K]$	Convective heat transfer coefficient
Δp	$[kPa]$	Pressure drop
θ_p	$[deg]$	Tube layout angle

APPENDIX I

Summary of cost correlations for heat exchangers

Cost in 1982 US dollars and surface area in m² except where differently indicated.

Shell Type	Material (shell-tube)	Notes	Equation for capital investment estimation	Ref.	
Fixed tube-sheets	CS-CS	18 BWG 2.44 m – 3<S<17	$2 \cdot 10^{-3} \cdot S^2 + 8.25 \cdot 10^{-2} \cdot S + 1.524$	Hall et al., 1982	
		18 BWG 3.66 m – 5<S<19	$1.5 \cdot 10^{-3} \cdot S^2 + 9.08 \cdot 10^{-2} \cdot S + 1.369$		
		18 BWG 4.88 m – 7<S<21	$1.8 \cdot 10^{-3} \cdot S^2 + 6.03 \cdot 10^{-2} \cdot S + 1.514$		
		16 BWG 2.44 m – 27<S<75	$9.57 \cdot 10^{-2} \cdot S + 2.32$		
		16 BWG 3.66 m – 37<S<93	$-2 \cdot 10^{-4} \cdot S^2 + 1.07 \cdot S + 1.902$		
		16 BWG 4.88 m – 46<S<140	$-1 \cdot 10^{-4} \cdot S^2 + 9 \cdot 10^{-2} \cdot S + 1.913$		
	CS-SS	18 BWG 2.44 m – 3<S<23	$-2.9 \cdot 10^{-3} \cdot S^2 + 0.29 \cdot S + 1.519$		
		18 BWG 3.66 m – 5<S<23	$-2.7 \cdot 10^{-3} \cdot S^2 + 0.27 \cdot 10^{-2} \cdot S + 1.441$		
		18 BWG 4.88 m – 7<S<23	$-3.5 \cdot 10^{-3} \cdot S^2 + 0.28 \cdot S + 1.194$		
		16 BWG 2.44 m – 27<S<84	$-2 \cdot 10^{-4} \cdot S^2 + 0.19 \cdot S + 2.888$		
		16 BWG 3.66 m – 27<S<93	$-2 \cdot 10^{-4} \cdot S^2 + 0.18 \cdot S + 2.101$		
		16 BWG 4.88 m – 37<S<121	$-3 \cdot 10^{-4} \cdot S^2 + 0.18 \cdot S + 1.803$		
U-tube	CS-CS	18 BWG 2.44 m – 3<S<17	$3 \cdot 10^{-3} \cdot S^2 + 4.55 \cdot 10^{-2} \cdot S + 1.479$		
		18 BWG 3.66 m – 5<S<21	$1.1 \cdot 10^{-3} \cdot S^2 + 6.38 \cdot 10^{-2} \cdot S + 1.880$		
		18 BWG 4.88 m – 9<S<23	$4 \cdot 10^{-4} \cdot S^2 + 7.61 \cdot 10^{-2} \cdot S + 1.297$		
		18 BWG 2.44 m – 27<S<75	$-3 \cdot 10^{-4} \cdot S^2 + 0.13 \cdot S + 0.782$		
		18 BWG 3.66 m – 46<S<93	$-2 \cdot 10^{-4} \cdot S^2 + 0.11 \cdot S + 0.502$		
		18 BWG 4.88 m – 46<S<121	$-2 \cdot 10^{-4} \cdot S^2 + 9.35 \cdot 10^{-2} \cdot S + 0.825$		
	CS-SS	18 BWG 2.44 m – 3<S<23	$-2.3 \cdot 10^{-3} \cdot S^2 + 0.26 \cdot S + 1.472$		
		18 BWG 3.66 m – 5<S<23	$-2.1 \cdot 10^{-3} \cdot S^2 + 0.249 \cdot S + 1.106$		
		18 BWG 4.88 m – 7<S<23	$-1.6 \cdot 10^{-3} \cdot S^2 + 0.231 \cdot S + 0.981$		
		18 BWG 2.44 m – 27<S<65	$-6 \cdot 10^{-3} \cdot S^2 + 0.228 \cdot S - 0.402$		
		18 BWG 3.66 m – 37<S<103	$-1.3 \cdot 10^{-3} \cdot S^2 + 0.293 \cdot S + 0.413$		
		18 BWG 4.88 m – 37<S<121	$-6 \cdot 10^{-4} \cdot S^2 + 0.231 \cdot S + 1.006$		
Floating head	CS-CS	18 BWG 2.44 m – 3<S<17	$3.9 \cdot 10^{-3} \cdot S^2 + 6.77 \cdot 10^{-2} \cdot S + 1.771$		
		18 BWG 3.66 m – 5<S<19	$1 \cdot 10^{-3} \cdot S^2 + 0.105 \cdot S + 1.613$		
		18 BWG 4.88 m – 7<S<21	$4 \cdot 10^{-4} \cdot S^2 + 9.78 \cdot 10^{-2} \cdot S + 1.649$		
		18 BWG 2.44 m – 27<S<75	$-5 \cdot 10^{-4} \cdot S^2 + 0.18 \cdot S + 0.473$		
		18 BWG 3.66 m – 37<S<93	$-3 \cdot 10^{-4} \cdot S^2 + 0.14 \cdot S + 1.014$		
		18 BWG 4.88 m – 46<S<121	$-5 \cdot 10^{-4} \cdot S^2 + 0.17 \cdot S - 0.952$		
	CS-SS	18 BWG 2.44 m – 5<S<21	$-2.8 \cdot 10^{-3} \cdot S^2 + 0.36 \cdot S + 1.339$		
		18 BWG 3.66 m – 7<S<23	$-2.3 \cdot 10^{-3} \cdot S^2 + 0.32 \cdot S + 1.334$		
		18 BWG 4.88 m – 7<S<23	$-4.1 \cdot 10^{-3} \cdot S^2 + 0.34 \cdot S + 1.075$		
		18 BWG 2.44 m – 27<S<65	$-1.3 \cdot 10^{-3} \cdot S^2 + 0.31 \cdot S + 2.006$		
		18 BWG 3.66 m – 27<S<103	$-7 \cdot 10^{-4} \cdot S^2 + 0.26 \cdot S + 1.687$		
		18 BWG 4.88 m – 37<S<112	$-5 \cdot 10^{-4} \cdot S^2 + 0.24 \cdot S + 1.038$		
	CS-CS		$30800 + 750 \cdot S^{0.81}$	Hall et al. 1990 (1986 cost values)	
	CS-SS		$30800 + 1339 \cdot S^{0.81}$		
	SS-SS		$30800 + 1644 \cdot S^{0.81}$		
	CS-CS		$7000 + 360 \cdot S^{0.80}$	Taal et al., 2003	
	CS-SS		$8500 + 409 \cdot S^{0.85}$		
	SS-SS		$10000 + 324 \cdot S^{0.91}$		
FH-FX	CS-CS	T<340 °C P<10 bar Surface area in ft ²	$10205 + 11.52 \cdot S$	Loh et al., 2002. (1998 cost values)	

APPENDIX II

Summary of equations to compute material volume

Subassembly	Material Volume
Shell	$\pi \cdot \frac{(D_{S,i} + 2 \cdot t_S)^2 - D_{S,i}^2}{4} \cdot L_T$
Baffles	$D_{S,i}^2 \cdot \left[\pi \cdot \frac{1}{4} \cdot \left(1 - \frac{1}{\pi} \cdot k4 \right) + \frac{1}{2} \cdot \sin(k4) \cdot \left(\frac{1}{2} - Bc \right) \right] \cdot t_B \cdot N_B$
Tube-sheets	$\pi \cdot \frac{(D_{S,i} \cdot (1 + 2 \cdot Dr))^2}{4} \cdot t_{TS} \cdot N_{TS}$
Tubes	$\pi \cdot \frac{D_{T,o}^2 - (D_{T,o} - 2 \cdot t_T)^2}{4} \cdot L_T \cdot N_T$
Channels	$\pi \cdot \frac{(D_{S,i} + 2 \cdot t_S)^2 - D_{S,i}^2}{4} \cdot L_{CH} \cdot N_{CH}$
Removable cover	$\pi \cdot \frac{(D_{S,i} \cdot (1 + 2 \cdot Dr))^2}{4} \cdot t_{RC} \cdot N_{CH}$
Flanges	$\pi \cdot \frac{(D_{S,i} \cdot (1 + 2 \cdot Dr))^2 - D_{S,i}^2}{4} \cdot t_{FL} \cdot N_{FL}$

with $k4 = \cos^{-1} \left(\frac{0.5 - Bc}{0.5} \right)$

Summary of equations to compute processing length L_k

Operation	Rolledshell	Standard tube shell	Baffle	Flange
Plate Cutting/Bevelling	$2 \cdot (\pi \cdot D_{S,i} + W_{RP})$	-	$D_{S,i} \cdot [(\pi - k4) + \sin(k4)]$	$2 \cdot \pi \cdot D_{S,i} \cdot (1 + Dr)$
Tubes cutting	-	$\pi \cdot D_{S,o}$	-	-
Welding (longitudinal)	W_{RP}	-	-	-
Welding (circumferential)	$\pi \cdot D_{S,i} \cdot \left(1 + \frac{1}{N_{RP}} \right)$	$\pi \cdot D_{S,i} \cdot \left(1 - \frac{1}{N_{T,tr}} \right)$	-	-
Drilling	-	-	$\left[\left(1 - \frac{k4}{\pi} \right) + \frac{2}{\pi} \cdot \sin k4 \cdot \left(\frac{1}{2} - Bc \right) \right] \cdot t_B \cdot N_T$	$\left(\frac{\pi \cdot D_{S,i} \cdot (1 + Dr)}{bd} \right) \cdot t_{FL}$
Plate rolling	$\pi \cdot D_{S,i}$	-	-	-
Notes	For each of N_{RP} rolled plates	For each of $N_{T,tr}$ tube trunks	For each of N_B baffles	For each of N_{FL} flanges

Summary of equations to compute processing length L_k (continued)

Operation	Tube-sheet	Channel (Rolled)	Channel (stdshell)	Removable cover	Tube
<i>Plate Cutting/Bevelling</i>	$\pi \cdot D_{S,i} \cdot (1 + 2 \cdot Dr)$	$2 \cdot (\pi \cdot D_{S,i} + W_{CH})$	-	$\pi \cdot D_{(S,i)} \cdot (1 + 2 \cdot Dr)$	-
<i>Tubes cutting</i>	-	-	$\pi \cdot D_{S,o}$	-	$\pi \cdot D_{T,o}$ (*)
<i>Welding (longitudinal)</i>	-	W_{CH}	-	-	-
<i>Welding (circumferential)</i>	-	$2 \cdot \pi \cdot D_{S,o}$	$2 \cdot \pi \cdot D_{S,o}$	-	$\pi \cdot D_{T,o} \cdot N_{T,tr}$ (*)
<i>Drilling</i>	$\left(N_T + \frac{D_{S,i} \cdot (1 + Dr)}{bd} \right) \cdot t_{TS}$	-	-	$\frac{D_{S,i} \cdot (1 + Dr)}{bd} \cdot t_{RC}$	-
<i>Plate rolling</i>	-	$\pi \cdot D_S$	-	-	-
<i>Notes</i>	For each of N_{TS} tube-sheets	For each of N_{CH} channel end		For each of N_{RC} removable cover	For each of N_T tube; (*) if necessary

Summary of equations to compute sub-assemblies occupied volume (i.e. to estimate costs of thermal treatments or transportation and handling)

Subassembly	Overall Volume
<i>Shell</i>	$\pi \cdot \frac{(D_{S,i} + 2 \cdot t_S)^2}{4} \cdot L_T$
<i>Baffle</i>	$D_{S,i}^2 \cdot \left[\frac{\pi}{4} \cdot \left(1 - \frac{k4}{\pi} \right) + \frac{1}{2} \cdot \sin(k4) \cdot \left(\frac{1}{2} - Bc \right) \right] \cdot t_B$
<i>Tube-sheet</i>	$\pi \cdot \frac{(D_{S,i} \cdot (1 + 2 \cdot Dr))^2}{4} \cdot t_{TS}$
<i>Tube</i>	$\pi \cdot \frac{D_{T,o}^2}{4} \cdot L_T$
<i>Channel</i>	$\pi \cdot \frac{(D_{S,i} + 2 \cdot t_S)^2}{4} \cdot L_{CH}$
<i>Removable cover</i>	$\pi \cdot \frac{(D_{S,i} \cdot (1 + 2 \cdot Dr))^2}{4} \cdot t_{RC}$
<i>Flange</i>	$\pi \cdot \frac{(D_{S,i} \cdot (1 + 2 \cdot Dr))^2}{4} \cdot t_{FL}$

Summary of equations to compute outer surface area of sub-assemblies

Subassembly	Outer Surface Area
<i>Shell</i>	$\pi \cdot D_{S,i} \cdot L_T$
<i>Baffle</i>	$D_{S,i} \cdot [(\pi - k4) + \sin(k4)] \cdot t_B + \pi \cdot \frac{D_{S,i}^2}{2} \cdot \left(1 - \frac{k4}{\pi}\right) + \frac{D_{S,i}^2}{2} \cdot \sin(k4) \cdot \left(\frac{1}{2} - Bc\right)$
<i>Tube-sheet</i>	$\pi \cdot \frac{(D_{S,i} \cdot (1 + 2 \cdot Dr))^2}{2} + \pi \cdot D_{S,i} \cdot (1 + 2 \cdot Dr) \cdot t_{TS}$
<i>Tube</i>	$\pi \cdot D_{T,o} \cdot L_T$
<i>Channel</i>	$\pi \cdot (D_{S,i} + 2 \cdot t_s) \cdot L_{CH}$
<i>Removable cover</i>	$\pi \cdot D_{S,i} \cdot (1 + 2 \cdot Dr) \cdot t_{RC} + \pi \cdot \frac{(D_{S,i} \cdot (1 + 2 \cdot Dr))^2}{2}$
<i>Flange</i>	$\pi \cdot \frac{(D_{S,i} \cdot (1 + 2 \cdot Dr))^2 - D_{S,i}^2}{2} + \pi \cdot [D_{S,i} \cdot (1 + 2 \cdot Dr) + D_{S,i}] \cdot t_{FL}$

APPENDIX III

Material volume estimation for channel-type end plates

End plates, when having a "channel" configuration are made up of a rolled plate or a tube trunk of length L_{CH} connected to two extremal flanges. One flange is bolted to the corresponding tube-sheet and shell, while the other is bolted to a removable removable cover. Materials volume for channels is estimated as done for the shell but factoring in the channel length L_{CH} instead of the shell length.

$$V_{CH,mat} = \pi \cdot \frac{(D_{S,i} + 2 \cdot t_S)^2 - D_{S,i}^2}{4} \cdot L_{CH} \cdot N_{CH} \quad (49)$$

Material volume for the removable covers, having a thickness t_{RC} , is given instead by

$$V_{RC,mat} = \pi \cdot \frac{(D_{S,i} \cdot (1 + 2 \cdot Dr))^2}{4} \cdot t_{RC} \cdot N_{CH} \quad (50)$$

being N_{CH} the channels number.

Material volume estimation for flanges

Flanges material volume, including volume to be subsequently drilled, is

$$V_{F,mat} = \pi \cdot \frac{(D_{S,i} \cdot (1 + 2 \cdot Dr))^2 - D_{S,i}^2}{4} \cdot t_{FL} \cdot N_{FL} \quad (51)$$

being N_{FL} the flanges number.

Material volume estimation for tie rods

$$V_{td} = N_{td} \cdot \pi \cdot \frac{D_{td}^2}{4} \cdot (L_T - L_{bc})$$

being N_{td} the number of tie rods and D_{td} their diameter. Tie rod insertion cost is computed determined as done for a tube insertion.

Material volume estimation for spacers

$$V_{sp} = N_B \cdot \pi \cdot \frac{D_{sp,e}^2 - D_{sp,i}^2}{4} \cdot L_{bc} \cdot N_{td}$$

where $D_{sp,e}$ and $D_{sp,i}$ are respectively the external and internal spacers diameter. Spacers have to be individually inserted on each tie rod in the space between baffles. The insertion cost is determined by labor time consumption cost only, as

$$C_{op_{in,sp}} = N_B \cdot N_{td} \cdot T_{in,sp} \cdot LR$$

being $T_{in,sp}$ is the time required to insert a single spacer by one operator.

Bolting cost

Bolts cost C_{bt} depend from the unit cost C_{bt} and from their number N_{bt}

$$C_{bt} = N_{bt} \cdot C_{bt}$$

Bolts insertion and tightening cost is determined by labor time consumption cost only, as

$$C_{op_{bt}} = inf.int. \left(\frac{\pi \cdot D_{S,i} \cdot (1 + Dr)}{bd} \right) \cdot LR \cdot 2 \cdot N_{ts} \cdot T_{in,bt} \cdot LR$$

being $T_{in,bt}$ is the time required to insert and tighten a single bolt by one operator.

Detailed estimation of manufacturing operations

A more detailed general purpose equation to estimate processing cost, instead of Eq. (11), is (Creese and Adithan, 1992)

$$C_{op} = \sum_{k=1}^K \left[\frac{L_k}{v_k} \cdot C_{H,k} + (C_{H,L,k} + C_{H,E,k}) \cdot \left(T_{LU,k} + \frac{T_{su,k}}{BS} \right) + \frac{C_{AUX}}{BS} \right] \quad (52)$$

which include fixed operations cost, such us setup and loading/unloading cost or fixed auxiliary costs as well as batch size. In Eq. (52) T_{LU} is the load/unload time of the part to be processed, T_{su} is the set up time, BS is the batch size, and C_{AUX} any auxiliary set up related fixed cost.

When operations involving a surface processing (i.e. painting) instead of a linear processing (like cutting or welding) are to be estimated the term L_k is to be substituted with the surface area S_k of the workpiece, while the processing velocity v_k assumes the meaning of a processed surface per unit time (m²/h).

In case of a drilling operation, apart from drilling thickness t , the actual tool travel length L_d should include even pre-travel L_{pt} , over-travel L_{ot} , and lead L_l lengths i.e.

$$L_d = L_{pt} + t + L_{ot} + L_l \quad (53)$$

while the processing speed v_d depends on the spindle rotational speed ω and the feed rate fr which, in turn, depend from tool and workpiece material and thickness (Creese and Adithan, 1992)

$$v_d = fr \cdot \omega = fr \cdot \frac{60 \cdot c_{c,d}}{\pi \cdot D_h} \quad (54)$$

being $v_{c,d}$ the drilling velocity and D_h the hole diameter.

In case of welding operations the hourly operation cost includes operator cost, electrode consumption cost, inert gas cost or flux cost, and energy cost. Thus Eq. (12) should be rewritten as

$$C_{H,w} = C_{H,L,w} + C_{H,E,w} + \left(\frac{WFR \cdot EWL \cdot EC}{EMY} + WMD \cdot FCR \cdot FC \cdot v_w + \frac{WC \cdot WV \cdot c_{kWh}}{WE} \right) \quad (55)$$

where WFR is the wire feed rate, EWL the electrode weight per unit length, EC the specific electrode cost, EMY the deposition efficiency ratio, WMD the deposited weld metal per unit length, FCR the flux consumption rate, FC the flux specific cost, v_w the welding velocity, WC the welding current intensity, WV the welding voltage, WE the welding electric efficiency and c_{kWh} the electricity cost.

However, in case inert gas is used instead of flux the term ($WMD \cdot FCR \cdot FC \cdot c_w$) should be replaced by ($GFR \cdot GC$), being GFR the gas flow rate and GC the specific gas cost.