ISSN 2176-5480

22nd International Congress of Mechanical Engineering (COBEM 2013)
November 3-7, 2013, Ribeirão Preto, SP, Brazil
Copyright © 2013 by ABCM

A DETAILED COST ESTIMATION MODEL FOR HEAT EXCHANGERS

Antonio C. Caputo
University of Roma Tre, Via della Vasca Navale, 79, Roma, 00146, Italy.
acaputo@uniroma3.it

Pacifico M. Pelagagge
University of L'Aquila, Zona industriale di Pile, L'Aquila, 67100, Italy.
pacifico.pelagagge@univaq.it

Paolo Salini
University of L'Aquila, Zona industriale di Pile, L'Aquila, 67100, Italy.
paolo.salini@univaq.it

Abstract. *Traditional costing methods for shell and tube heat exchangers rely on simple parametric functions, mostly based on the sole overall heat transfer surface, and are applicable to traditional equipment configurations in limited size ranges only. 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. In fact, parametric functions are unable to assess the effect on the overall cost of detailed design decision or changes in the equipment architecture. Moreover, they are not detailed enough to be used in computerized design optimization procedures. In order to provide a more precise costing approach, in this paper a generative – analytical cost estimation procedure for shell and tube heat exchangers is developed. This allows to obtain a costing procedure linked to detailed geometrical features and manufacturing processes which is better suited to computerized design and economic optimization of heat exchangers. It can also be used for precise cost estimation during competitive bidding in make to order manufacturing context. A comparison of the proposed costing method and traditional parametric correlations is also included resorting to numerical examples.*

Keywords: *Shell & 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; Geiger and Dilts, 1996). 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 bears the risk of making the firm uncompetitive and losing a customer, while underestimating the cost leads to winning a contract but incurring a financial loss (Caputo and Pelagagge, 2008). 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 (Elg and Cederfelt, 2007; Noble and Tanchoco, 1990; Oh and Park, 1993). Finally, when engineers try to optimize the architecture of a product by changing the values of design parameters so that the investment cost and operating costs are minimized, they often rely on sophisticated 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 optimization techniques, such as genetic algorithms, able to handle a large number of design parameters including both discrete and continuous variables (Babu and Munawar, 2007; Caputo et al., 2008; Hilbert et al., 2006; Ponce-Ortega et al., 2009; Tayal et al., 1999). 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 basing only on 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.

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.

ISSN 2176-5480

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. Finally, an application example is provided to compare the proposed costing method with the traditional one.

2. HEAT EXCHANGERS COSTING METHODS

Quantitative cost estimating methods are usually classified into statistical models, analogous models or generative-analytical models (Caputo and Pelagagge, 2008; Layer et al., 2002; Foussier, 2006; Stewart and Wyskida, 1987; 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. However, artificial neural networks (ANN) have also been employed thanks to their ability to classify, summarize and extrapolate collections of data also showing superior performances respect traditional parametric methods (Caputo and Pelagagge, 2008; Bode, 2000; Cavalieri et al., 2004; Shtub and Zimmermann, 1993; Mason and Smith, 1997; Wang et al., 2000).

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 products. Finally, they require historical data which are usually 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. 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.

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. Alternatively, case based reasoning and expert systems also rely on similarities between products to generate estimates and are effective in case of modular products with variants (An et al., 2007; Duverlie and Castelain, 1999). 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.

Generative-analytical methods are the most accurate in that they try to depict the actual product creation process. A detailed analysis of the production process and decomposition into single manufacturing operations is, in fact, carried out. 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 and 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). Analytical techniques even form the basis of Design-for-Manufacturing methods, and provide detailed models for single technological processes (Boothroyd et al., 2001; Poli, 2001). However, analytical models, utilize a very large amount of information, and are much more time consuming as they require a detailed design of the product and processes knowledge, often resulting difficult to implement and utilize.

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 were parametric equipment costing methods are historically well established. However, the accuracy of such models is often quoted in the ± 10% to ± 30% range. The basic parameters involved in parametric cost functions 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 (Hall et al., 1990; Taal et al., 2003). An example of a cost function for stainless steel

ISSN 2176-5480

exchangers is given as

$$E_C = 13324 + 431 \cdot A^{0.91} \tag{1}$$

where E_C 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 and size ranges.

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,

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

while the cost of the actual exchanger is E_C = 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, ¾ (in) tubes with pitch to diameter ratio of 1.25, length of 6.1 m and operating pressure up to 6.8 bar) as

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

and compute the actual equipment cost as E_C = 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.

A further evolution of parametric-analogous approach is the Purohit method which represents one of the most detailed and sophisticated heath exchanger costing estimation technique available to date. It has an error margin lower than ±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 ¾" 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

$$b = \left[\frac{6.6}{1 - e^{[(7 - D_S)/27]}}\right] p\ f\ r \tag{4}$$

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_{Ntp} (tube passes, when greater than 2), C_{PS} (shell side pressure), C_{PT} (tube side pressure) correction when internal pressure 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

$$E_C = b\left(1 + \sum_i C_i\right) A \tag{5}$$

Finally, it should be reported that even ANN techniques have been recently applied to heat exchanger cost estimation (Duran et al., 2009).

However, 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 when the same surface area is maintained;
- do not reflect actual manufacturing cost but rather the purchased equipment cost, which are influenced by market scenarios;
- some authors present correlations which are valid in a limited size range (for instances Hall's correlations apply to surface areas lower than 140 m^2);
- 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

This is especially critical when excessively simplified cost functions, such as Hall correlations (Eq. 1), are used as a basis to build 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. This also implies a different weight of the labour costs, which Purohit (Purohit, 1982) demonstrated to be the main cost item in heat exchanger manufacturing. Furthermore, exchangers designed according to standard methods tend to have a length to diameter ratio between 3 and 15, but 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. 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, a generative analytic approach will be applied in the following section.

3. HEAT EXCHANGERS COST MODEL DEVELOPMENT

This procedure is referred to the AEL TEMA type heat exchanger, with one shell and tube pass and front and rear end channel type (Fig. 1). 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 relationship for process operations, instead has been freely adapted from (Creese and Adithan, 1992).

The manufacturing cost of the heat exchanger (CHE) can be computed as the sum of the materials and manufacturing cost (Cc_i) of its main i-th subassemblies, namely i = 1: shell; i = 2: channels; i = 3: tube sheet; i = 4: baffles; i = 5: tubes bundle, as shown in Eq (1) and Figure 1.

$$CHE = \sum_{i=1}^{Nit} Cc_i \tag{6}$$

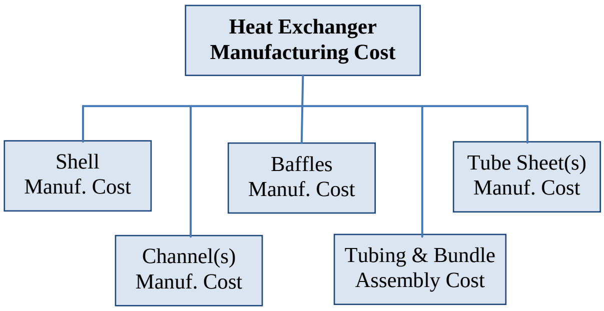

Figure 1. Scheme of heat exchanger manufacturing cost decomposition.

In turn, 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 is carried out in a parametric manner by knowing the set of main geometrical features of the heat

ISSN 2176-5480

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 tubesheets; thickness and diameter of shell flanges.

In Eq. (1) the cost of each subassembly is defined as

$$Cc_i = Cmat_i + \sum_{k=1}^{Nop} Cop_k \tag{7}$$

where Cop_k is the cost of the k-th manufacturing operation required by the i-th subassembly, as detailed later, and N_{op} is ghe number of different operations required by each subassembly, while

$$Cmat_i = Vol_i \cdot r \cdot Cmu \tag{8}$$

is the material cost estimated as the material volume times the density and material unit cost. Volume of each subassembly can be estimated resorting to formulas in Table 1. The reader can refer to the nomenclature for details on the symbols meaning.

Table 1. Summary of equations to compute material volumes of exchanger main subassemblies.

Subassembly	Material volume
Shell	$\pi \cdot \frac{D_s{}^2 - (D_s - 2 \cdot t_s)^2}{4} \cdot L_{tt} + N_{fl} \cdot V_{fl}$
Baffles	$\left(\left(2 \cdot \sqrt{\left(\frac{D_s}{2}\right)^2 - \left(\frac{D_s}{2} - Bc \cdot D_s\right)^2} + \frac{D_s}{2} \cdot \alpha\right) - (N_{tt} - N_{ctw}) \cdot \pi \cdot \frac{D_t{}^2}{4}\right) \cdot Bthick \cdot Nb$
Tube Sheets	$\frac{\pi}{4} \cdot \left(D_{ex}{}^2 - \left(N_{tt} \cdot D_t{}^2 + N_{hc} \cdot D_{hc}{}^2\right)\right) t_{TS} \cdot$
Tubes	$\pi \cdot \frac{D_t{}^2 - (D_t - 2 \cdot t_t)^2}{4} \cdot L_{tt} \cdot N_{tt}$
Channels	$\left(\pi \cdot \frac{D_s{}^2 - (D_s - 2 \cdot t_s)^2}{4} \cdot L_{ch} + N_{fl} \cdot V_{fl}\right) \cdot N_{ch}$

In order to estimate manufacturing operations cost the manufacturing process for each subassembly should be defined at first. Figure 2 depicts the manufacturing process for the shell.

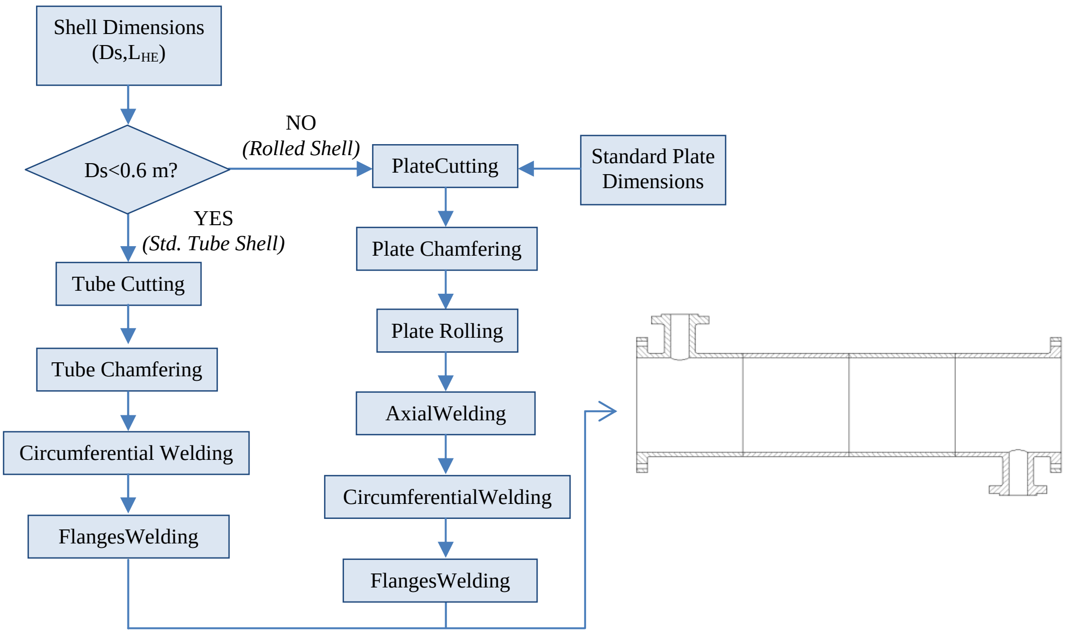

Figure 1. Scheme of shell manufacturing process.

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 2. Baffles are often 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.

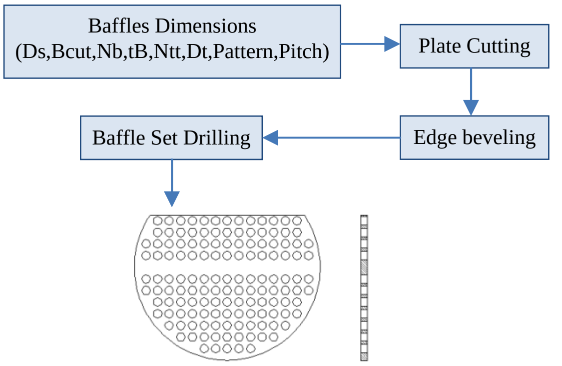

Figure 2. Scheme of baffle manufacturing process.

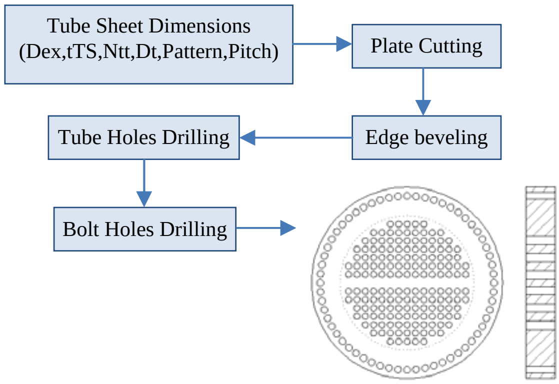

Figure 3. Scheme of Tube sheet manufacturing process.

The tube sheets in AEL heat exchangers are generally two. However, it is possible to have a double plate construction. The proposed approach is used to compute the cost of each tube sheet according to the process depicted in Figure 3. 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 of 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 4) very similar to the shell body (Figure 1), the same estimation procedure can be used, referring to the channel length L_{CH} instead of L_{HE}. 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.

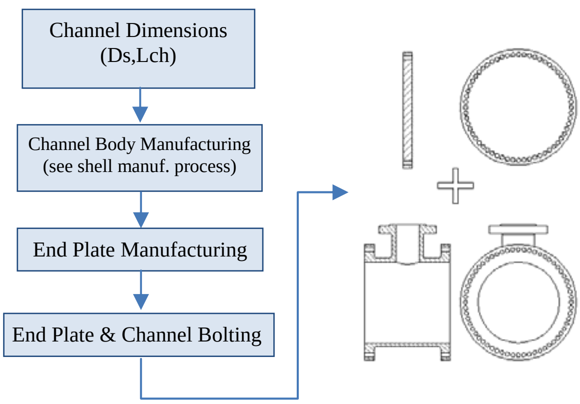

Figure 4. Scheme of tube sheet manufacturing process.

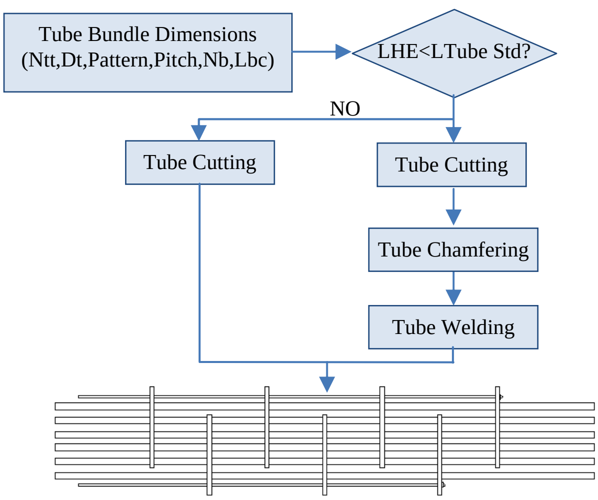

Figure 5. Scheme of tube bundle assembly process.

Passing to the tubes bundle fabrication, 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 in 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.

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.

A single cost estimation equation can be utilized to evaluate cost of the generic k-th operation involving cutting, beveling and rolling processes, as shown in Eq. 4,

$$Cop_k = \left[\left(\frac{L_k}{3600 \cdot Vop_k} + \frac{Tsu}{60 \cdot BS} + \frac{Tlul}{3600}\right) \cdot (Chw + LC) + Clul + \frac{Csu}{BS}\right] \cdot N_K \tag{9}$$

where L_k is the characteristic length of the worked part or the manufacturing process, Vop_k the process velocity, Tsu the setup time, Tlul the workstation load/unload time, Chw the hourly workstation cost, LC the hourly labor cost, Clul the fixed cost of the loading/unloading operations (since this operation requires dedicated people and/or equipment), BS the batch size, Csu the setup materials cost (i.e. consumables), and N_k the number of parts undergoing the same k-th operation.

The welding process cost, instead is computed as the sum of fixed (setup) and variable costs, the latter including labor, filler material, protective material (gas or flux), energy consumption. Variable costs are here expressed per unit length (€/m) and should be multiplied by the length of the weld. Amortization cost of the welding equipment should be then added to variable costs and is computed on the basis of the duration of the welding operation.

Specific labor cost is

$$LC_W = \frac{LC}{\cdot \frac{3600}{1000} S \cdot OF} \tag{10}$$

filler material cost is

$$VEC = \frac{WFR \cdot EWL \cdot EC}{S \cdot \frac{60}{1000} EMY} \tag{11}$$

consumed protective material cost is

$$VSC = \begin{cases} \dfrac{GFR \cdot GC}{S \cdot \frac{3600}{1000}} & (gas) \\ WMD \cdot FCR \cdot FC & (flux) \end{cases} \tag{12}$$

energy consumption cost is

$$VPC = \frac{I \cdot V \cdot PC/1000}{S \cdot \cdot \frac{3600}{1000} \cdot M} \tag{13}$$

Thus the cost of each welding operation is

$$Cop = Lk \cdot (LC_W + VEC + VSC + VPC) + \frac{C_{SU}}{DB} + Clul + \left(\frac{Tlul}{3600} + \frac{Lk}{3.6 \cdot S}\right) \cdot CRw \tag{14}$$

where CRw is the hourly amortization cost of the equipment and L_k is the weld length.

As far as the drilling operation is concerned it is required to make holes in both the baffles and tube sheets. As already said the baffles are stacked together until the maximum drilling length is reached and then are drilled simultaneously. Instead tube sheets are drilled separately and need both holes for tubes and bolts to connect them to shell and heads. We assume that drills have a single spindle and that a repositioning time is needed to move from the location of a hole to the next one in the sequence. The hole length is the sum of the pretravel, the lead, the thickness of the plate(s) to be drilled (t_B), and the overtravel

$$L_k = t_{pre} + t_B + lead + t_{over} \tag{15}$$

and the drilling velocity is a function of the material (see Table 2)

Table 2. Suggested drilling velocity

Material	**Cutting velocity Cvel (m/min)**
soft cast iron	45
medium cast iron	25
mild steel	27
alloy steel	18
tool steel	15
brass and bronze	60
copper	45
alluminum and magnesium alloys	105

The spindle rotational speed (rpm) is

$$N = \frac{1000 \cdot Cvel}{\pi \cdot dh} \tag{16}$$

while the drill tool feed rate is a function of material and hole diameter (dh) as shown in Table 3.

Table 3. Suggested drilling feed rate

Material description	**Feed rate (fr)**
Free machining materials	0.02 d_h
Tough or hard materials	0.01 d_h
Very hard materials	0.005 d_h

The drill tool advancement velocity is then

$$Fh = fr \cdot N \tag{17}$$

so that the drilling time can be computed as

$$Th = \frac{L_k}{Fh} \tag{18}$$

and the cost of any tube sheet or baffles set drilling (note that for tube sheets is BS = 1) is

$$Cop = \frac{C_{SU} + Clul}{BS} + \left(\frac{Tlul + (Th + Tmd) \cdot Nh}{3600 \cdot BS}\right) \cdot (LC + CRd) \tag{19}$$

ISSN 2176-5480

In the above equations the length characteristic of each process operation depends from the geometrical characteristics of the worked part as detailed in Table 4.

Table 4. Characteristic lengths L_k of process operations

Operation	Rolled shell	Standard tube shell	Baffles	Tube sheet
Plate Cutting	$2 \cdot (\pi \cdot D_s + hf)$	-	$\left(2 \cdot \sqrt{\left(\frac{D_s}{2}\right)^2 - \left(\frac{D_s}{2} - Bc \cdot D_s\right)^2} + \frac{D_s}{2} \cdot \alpha\right)$	$(\pi \cdot D_{ex})$
Tubes Cutting	-	$\pi \cdot Ds$	-	-
Chamfering	$2 \cdot (\pi \cdot D_s + hf)$	$\pi \cdot Ds$	-	$(\pi \cdot D_{ex}) \cdot$
Longitudinal Welding	hf	-	-	-
Circumferential Welding	$\pi \cdot D_s + \frac{1}{Nf}$	$\pi \cdot Ds$	-	-
Drilling	-	-	$Bthick \cdot (Ntt - Nctw)$	$t_{TS} \cdot Ntt \quad (Dt)$ $t_{TS} \cdot Nhc \cdot \quad (Dhc)$
Plate Rolling	$\pi \cdot D_s$	-	-	-
Notes	For each of Nf rolled plates	For each of tube trunks	For each of Nb baffles	For each of Nts tube sheets

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 metod 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.

4. APPLICATION EXAMPLE

In order to show the sensitivity of the above costing method to changes in the equipment constructive details, we compute the cost variations of a sample heat exchanger, having a surface area of 300 m^2, when the internal architecture is changed by varying the tubes diameter in the range from 10 to 51 mm and when the shell diameter is increased from 500 to 1500 mm. All plotted costs refer to exchangers having a triangular pitch, a pitch value of 1.25 Dt, Ltt/Ds ratio comprised between 3 and 15 (i.e exchangers having common values of length to diameter ratio), and for each equipment length a number of baffles equal to the average between minimum and maximum possible values. For each exchanger the geometrical characteristics have been computed, on the basis of the imposed value of heat transfer area, the tubes diameter and shell length, resorting to TEMA rules. Costs have been computed assuming a hourly machine cost of 15 €/h, a hourly labour cost of 30 €/h, a material cost between 3 and 4 €/kg, and a machine setup time of 20 min. Such cost values are also compared with the (invariant) cost estimated by Hall's correlation CHE (€) = (11800+383 $S^{0.91}$), escalated to current values of the cost index and translated from US \$ to Euro. However, to provide a calculation comparable to the Hall's estimate, which refers to the FOB market price, an overhead rate of 20% has been considered, and a 30% mark-up has been added. Nevertheless, the point here is not to compare absolute cost values from different estimation methods, but rather to assess the sensitivity of the cost estimation methods to design changes. One observes in Figure 6 that while Hall's estimate, being based on the overall surface area, remains obviously unchanged, the proposed costing method is quite responsive to modification in the constructive details and that variations in the range +51% / -22% respect the average cost of 80600 € (Hall's estimate) are obtained simply changing some design parameters. This confirms that the proposed method, while providing more realistic estimates than traditional parametric functions, can even provide guidance to designers when finalizing the equipment architecture during the design phase in order to pursue a cost minimization.

5. CONCLUSIONS

In this work a quick and easy to use, but detailed cost estimation method for shell and tube heat exchangers has been presented. It is based on a generative -analytic 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 used as a more precise alternative to traditional costing methods based on statistical correlations 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.

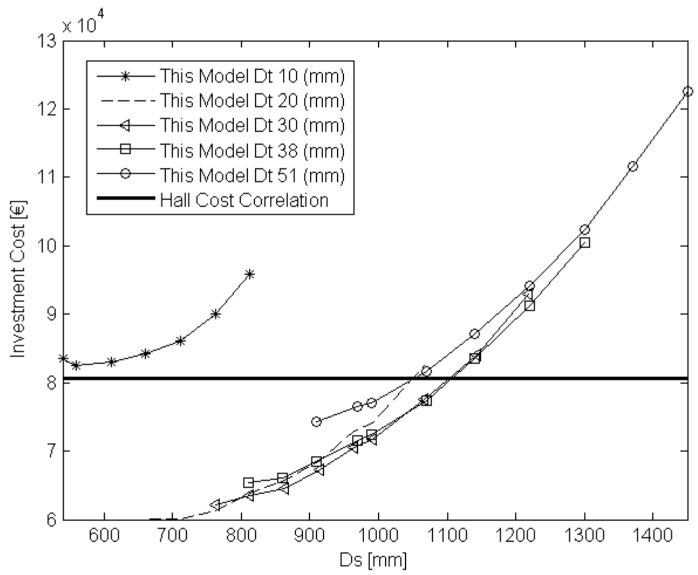

Figure 6. Sensitivity of exchanger cost to changes of geometrical architecture.

6. REFERENCES

An, S.H., Kim, G.H. and Kang, K.I.,2007. "A case-based reasoning cost estimating model using experience by Analytic Hierarchy Process". *Building and Environment*, Vol. 42, No. 7, pp. 2573-2579.

Babu, B.V. and Munawar, S.A.,2007. "Differential evolution strategies for optimum design of shell and tube heat exchangers". C*hemical Engineering Science*, Vol. 62, pp. 3720-3739.

Bode, J., 2000. "Neural networks for cost estimation: Simulation and pilot applications". *International Journal of Production Research*, Vol. 38, n. 6, pp. 1231-1254.

Boothroyd, G., Dewhurst, P. and Knight, W., 2001. *Product Design for Manufacture & Assembly*, Marcel Dekker, USA.

Caputo, A.C. and Pelagagge, P.M., 2008. "Parametric and neural methods for cost estimation of process vessels". *International Journal of Production Economics*, Vol. 112, Issue 2, pp. 934-954.

Caputo, A.C., Pelagagge, P.M. and Salini, P.,2008. "Heat exchangers design based on economic optimization". *Applied Thermal Engineering*, Vol. 28 , pp. 1151–1159.

Cavalieri, S., Maccarrone, P. and Pinto, R., 2004. "Parametric vs. neural network models for the estimation of production costs: A case study in the automotive industry", *International Journal of Production Economics*, Vol. 91, pp.165-177.

Corripio, A.B., Chrien, K.S., and Evans, L.B., 1995. "Estimate cost of heat exchangers and storage tanks via correlations". *Chemical Engineering*, Vol. 19, pp 125-127.

Creese, R. and Adithan, M., 1992. *Estimating and Costing for the Metal Manufacturing Industries*, CRC.

Dewhurst, P. and Boothroyd, G.,1989. "Early cost estimating in product design". *Journal of Manufacturing Systems*, pp. 183-191.

Duverlie, P. and Castelain, J.M.,1999. "Cost estimation during design step: Parametric method versus case based reasoning method". *International journal of Advanced Manufacturing Technology*, Vol. 15, no. 12, pp. 895-906.

Elgh, F. and Cederfeldt, M., 2007. "Concurrent cost estimation as a tool for enhanced producibility. System development and applicability for producibility studies". *International Journal of Production Economics*, Vol. 109, pp.12-26.

Foussier, P.M.M., 2006. *From Product Description to Cost: A Practical Approach*, Springer.

Geiger, T.S. and Dilts, D.M., 1996. "Automated design-to-cost: Integrating costing into the design decisions". *Computer Aided Design*, Vol. 28, pp. 423-438.

Hall, R.S., Ahmad, S. and Smith, R., 1990. "Capital cost targets for heat exchanger networks comprising mixed materials of construction, pressure ratings and exchanger types". *Chemical engineering*, Vol. 14, pp.319-335.

Hilbert, R., Janiga, G., Baron, R. and Thevenin, D., 2006. "Multi-Objective shape optimization of a heat exchanger using parallel genetic algorithm". *International Journal of Heat and Mass Transfer*, Vol. 48, pp. 2567-2577.

Kingsman, B., Hendry, L., Mercer, A. and de Souza, A.,1996. "Responding to customer enquiries in make-to-order companies. Problems and solutions". *International Journal of Production Economics*, Vol. 46-47, pp. 219-231.

Kuppan, T. 2000. *Heat Exchanger Design Handbook*, CRC.

Layer, A., Brine, E.T., Van Houten, F., Kals, H. and Haasis, S., 2002. "Recent and future trends in cost estimation". *International Journal of Computer Integrated Manufacturing*, Vol. 15, n. 6, pp. 499-510.
Mason, A.K. and Smith, A.E., 1997. "Cost estimation predictive modeling: Regression vs neural network". *The Engineering Economist*, Vol. 42, n. 2, pp. 137-162.
Niazi, A., Dai, J.S., Balabani, S. and Seneviratne, L., 2006. "Product cost estimation: technique. Classification and methodology review". *ASME Transactions J. Manuf. Sci. and Eng.*, Vol. 128, No. 2, pp. 563 -575.
Noble, J.S. and Tanchoco, J.M.A.,1990. "Concurrent design and economic justification in developing a product". *International Journal of Production Research*, Vol. 28, n. 1, pp. 1225-1238.
Oh, C.J. and Park, C.S., 1993. "An economic evaluation model for product design decisions under concurrent engineering". *The Engineering Economist*, Vol. 38, n. 4, pp. 275-296.
Ou-Yang, C. and Lin, T.S.,1997. "Developing an integrated framework for feature-based early manufacturing cost estimation". *Advanced Manufacturing Technology*, Vol. 13, n. 9, pp. 618-627.
Poli, C., 2001. *Design for Manufacturing*, Butterworth-Heinemann.
Ponce-Ortega, J.M., Serna-Gonzalez, M. and Jimenez-Gutierrez, A., 2009. "Use of genetic algorithm for the optimal design of shell-and-tube heat exchangers". *Applied Thermal Engineering*, Vol. 29, pp. 203-209.
Purohit, G.P., 1982. "Estimating costs of shell and tube heat exchangers". *Chemical Engineering*, August, pp. 56-67.
Seider, W.D., Seader, J.D. and Lewin, D.R., 1999. *Product & Process Design Principles*, Wiley.
Shehab, E. and Abdalla, H., 2002a. "A design to cost system for innovative product development". *Proc. Instn. Mech. Engrs, Part B, Journal of Engineering Manufacture*, Vol. 216, pp. 999-1019.
Shehab, E. and Abdalla, H., 2002b. "An intelligent knowledge-based system for product cost modelling". *International Journal of Advanced Manufacturing Technology*, Vol. 19, pp. 49-65.
Shtub, A. and Zimmermann, Y., 1993. "A neural network based approach for estimating the cost of assembly systems". *International Journal of Production Economics*, Vol. 32, n. 2, pp. 189-207.
Stewart, R.D. and Wyskida, R.M., 1987. *Cost Estimator's Reference Manual*, Wiley, New, York.
Taal, M., Bulatov, I., Klemes, J. and Stehlik, P., 2003. "Cost estimation and energy price forecast for economic evaluation of retrofit projects". A*pplied thermal engineering*, Vol. 23 pp. 1819-1835.
Tayal, M.C. , Fu, Y. and Diwekar, U.M., 1999. "Optimal design of heat exchangers: A genetic algorithm framework". *Ind. Eng. Chem. Res.*, Vol. 38, pp. 456-467.
Wang, Q., Stockton, D.J. and Baguley, P.,2000. "Process cost modeling using neural networks". *International Journal of Production Research*, Vol. 38, n. 16, pp. 3811-3821.
Wierda, L.S., 1991. "Linking design, process planning and cost Information by feature based alignment". *Journal of Engineering Design*, Vol. 2, No. 1, pp. 3-18.
Duran, O., Rodriguez, N. and Consalter, L.A., 2009. "Neural networks for cost estimation of shell and tube exchangers". *Expert Systems with Applications*, Vol. 36, No. 4, pp. 7435-7440.

7. NOMENCLATURE

Symbol	**Unit of measure**	**Description**
Bc	*[%]*	Baffle cut percentage
BS	*[-]*	Batch size
Bthick	*[mm]*	Baffles thickness
Cc_i	*[€]*	Cost of the i-th heat exchanger component
CHE	*[€]*	Heat exchanger manufacturing cost
Chw	*[€/h]*	Hourly cost of the k-th machine operation
Clul	*[€/item]*	Unit handling cost per item (mechanized equipment)
Cmat	*[€]*	Material cost
Cmu	*[€/kg]*	Material cost per unit weight
Cop	*[€/item]*	Manufacturing process cost
CRd	*[€/h]*	Drill hourly cost (amortization pus energy consumption)
CRw	[€/h]	Hourly welding machine cost
Csu	*[€/setup]*	Setup material cost
Cvel	*[m/min]*	Cutting velocity
DC	[%]	Duty cycle
Dex	*[mm]*	Tube sheet external diameter
dh	*[mm]*	Hole diameter
Dhc	*[mm]*	Tube sheet circumferential holes diameter
DR	[kg/h]	Deposition rate
Ds	*[mm]*	Shell Diameter
Dt	*[mm]*	Tube diameter
EC	[€/kg]	Electrode cost
EMY	[-]	Electrode metal yield
EWL	[kg/m]	Electrode weight per unit length

ISSN 2176-5480

FC	[€/kg_{flux}]	Flux cost
FCR	[kg_{flux}/$kg_{wel.met.}$]	Flux consumption rate
Fh	*[mm/min]*	Feed rate (tool advancement speed)
fr	*[mm/rev]*	Feed per revolution
GC	*[€/m^3]*	Specific gas cost
GFR	[m/h]	Gas flow rate
H	[J/mm]	Energy per unit of weld length
hf	*[mm]*	Plate width
I	[A]	Welding Current
Nf	*[-]*	Plate number
L_k	*[mm/item]*	k-th operation characteristic dimension or operation length per part
LC	*[€/h]*	Labor cost
LC_W	*[€/m]*	Specific welding labor cost
Lch	*[mm]*	Channel length
Lead	*[mm]*	Hole lead
Lh	*[mm]*	Drilling length
LtStdMax	*[mm]*	Standard tube maximum length
Ltt	*[mm]*	Tube bundle length, Shell length
M	[-]	Machine efficiency
N	*[rpm]*	Drill rotational speed
Nb	*[-]*	Baffles Number
Nch	*[-]*	Channels number
Nctw	*[-]*	Tube number in baffle window
Nf	*[-]*	Plates number
Nfl	*[-]*	Flange number
Nh	*[-]*	Holes number
Nhc	*[-]*	Tube sheet circumferential holes number
Nit	*[-]*	Number of heat exchanger components
N_k	*[-]*	Number of identical parts undergoing the k-th process operation
Nm	*[-]*	Number of materials for the i-th HE component
Nop	*[-]*	Number of operations for the k-th HE component
Nts	*[-]*	Tube sheet number
Ntt	*[-]*	Total bundle tubes number
OF	[-]	Operator efficiency
PC	[€/kWh]	Power cost
S	[mm/s]	Welding speed
r	[kg/ m^3]	Material density
SWC	*[€/m]*	Specific welding cost
Th	*[s]*	Drilling Time
Tlul	*[s]*	Load and unload time
Tmd	*[s]*	Spindle repositioning time
t_{over}	*[mm]*	Drill overtravel
t_{pre}	*[mm]*	Drill pretravel
t_s	*[mm]*	Shell thickness
Tsu	*[min/setup]*	Setup time
t_t	*[mm]*	Tube thickness
t_{TS}	*[mm]*	Tube sheet thickness
V	[V]	Voltage
VEC	*[€/m]*	Filler material cost
Vfl	*[-]*	Flange Volume
Vopk	*[mm/s]*	Operation velocity of k-th process operation
Vol	*[m^3]*	Part volume
VPC	*[€/m]*	Energy consumption cost
VSC	*[€/m]*	Consumed protective material cost
WFR	[m/min]	Wirefeed rate
WMD	[kg/ *m]*	Weight of molten metal
WT	[min]	Welding time
α	*[rad]*	Baffle cut angle

8. RESPONSIBILITY NOTICE

The authors are the only responsible for the printed material included in this paper.