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MANUFACTURING COST OPTIMIZATION OF A SHELL AND TUBE HEAT EXCHANGER USING THE DIFFERENTIAL EVOLUTION ALGORITHM

Examiners: Professor Juha Varis
Professor Esa Vakkilainen

ABSTRACT

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Manufacturing cost optimization of a shell and tube heat exchanger using the differential evolution algorithm

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An optimization procedure is performed using the Differential Evolution algorithm to obtain the optimum thermohydraulic and mechanical design values of a shell and tube heat exchanger with the minimum cost of manufacturing. The objective cost functions are developed for two different case studies with two different groups of decision variables based on an analytical generative cost model. The results show that the selection of decision variables has a considerable effect on the obtained design values and estimated manufacturing cost. Shell and tube heat exchanger manufacturers can benefit the introduced approach for the design optimization and manufacturing cost minimization process.

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LIST OF SYMBOLS AND ABBREVIATIONS

Symbols

A	Area [m^2]
awh	Annual working hours [h]
b	Parameter limit [-]
BC	Baffle cut [%]
C	Cost [€ or $]
c	Heat capacity rate [W/K]
cp	Specific heat (isobaric) [kJ/kgK]
CR	Crossover constant [-]
D	Diameter [m]
F	Correction factor [-]
f	Function of [-]
H	Height of baffle cut [m]
h	Heat transfer coefficient (convective) [W/m^{2}K]
I	Investment cost [€]
k	Thermal conductivity [W/mK]
L	Length [m]
LGM	Ligament [m]
LR	Labor rate [€/h]
m	Number of workers [-]
$\dot{m}$	Flow rate [kg/s]
min	Minimum of [-]
N	Number of items
P	Power [kW]
Pr	Prandtl number [-]
q	Overall heat transfer rate [W]
R''	Thermal resistance per surface area [m^{2}K/W]
rnd	Random number [-]
S	Spacing [m]

s	Thickness [m]
$sup.int.$	Supremum integer of [-]
T	Temperature [°C]
t	Number of generation [-]
U	Overall heat transfer coefficient [W/m^{2}K]
V	Volume [m^3]
v	Velocity [m/h]
W	Width [m]
W_{HE}	Weight of heat exchanger [kg]
x	Vector of parameters [-]
y	Vector of parameters [-]
z	Vector of parameters [-]

Greek symbols

α	Exchanger type and material dependent coefficient [-]
β	Exchanger type and material dependent coefficient [-]
γ	Central angle of baffle cut [rad]
ρ	Density [kg/m^3]
θ	Tube layout [°]
μ	Dynamic viscosity [Pa·s]
τ	Capital recovery factor [%/yr.]
φ	Scaling coefficient [-]

Subscripts

ANC	Ancillary
amo	Amortization
avg	Average
b	beveling
bas	Basic
bfl	Baffle
c	Cutting
ch	Chamfering

chn	Channel
d	Drilling
$dshnd$	Dished end
eff	Effective
el	Electricity
EN	Energy
FOB	Free on Board
H	Hourly
hol	Holes
i	Index of vector
in	Inside
j	Index of parameter
k	Index of operation
L	Lower
l	Index of specific vector
m	Manufacturing
mat	Material
min	Minimum
O	Operating
o	Outside
op	Operation
otl	Outer tube limit
p	Actual operating pressure
plt	Plate
r	Rolling
sh	Shell
shp	Shell plate
$shtb$	Shell tube
st	Standard tube
$StdTb$	Shell standard tube
t	Tube
tot	Total

tp	Tube pass
tpp	Tubes per pass
ts	Tube sheet
typ	Exchanger type
U	Upper
w	Welding
x	Index of component

Abbreviations

ABC	Artificial Bee Colony
ASME	American Society of Mechanical Engineers
BS	British Standards
CSA	Cuckoo Search Algorithm
DE	Differential Evolution
GA	Genetic Algorithm
HTRI	Heat Transfer Research, Incorporation
ISO	International Standards Organization
LMTD	Logarithmic Mean Temperature Difference
NTU	Number of Transfer Units
PSO	Particle Swarm Optimization
SA	Simulated Annealing
TEMA	Tubular Exchanger Manufacturers Association

1 INTRODUCTION

Estimation of manufacturing cost is a necessary task in the design process and development of new products since a large portion of life-cycle costs are specified at the design level. After completion of the design level, there are few opportunities for cost reduction. Hence, having a prior estimation of cost can lead to the optimum selection of the design specifications and effective reduction of the total cost of the manufacturing process. (Weustink et al., 2000, p.141.)

1.1 Research background

Shell and tube heat exchangers are widely used in process industries due to their flexibility and variation in design, operation, and strength of construction. Considerable researches have been accomplished in recent decades to increase their thermal efficiency and improve their construction to make more profitable processes and reduce the energy loss. Their mechanical design has been constantly developed to accommodate the demands of various applications considering thermal, constructional, and safety requirements. (Schlünder, 1983, p.3.3.1_2; Fettaka et al., 2013, p.343.) Mechanical design of shell and tube heat exchangers which consists of two interlocked pressure vessels is a complex task which includes the design of shell, tube bundle, inlet and outlet headers, nozzles, and so on (Singh & Soler, 1984, p.1).

1.2 Research problem

In addition to all considerations to thermal design and construction of shell and tube heat exchangers, estimating the manufacturing cost of the optimum design is a major concern of manufacturers as they tend to minimize the cost while their final product meets the thermal, constructional, and pressure drop requirements, to overcome their competitors in the market. Most of the previous researchers neglected a lot of affecting cost parameters and only focused on minimizing the heat transfer surface area. A comprehensive approach to estimate the manufacturing cost of shell and tube heat exchangers considering all effective cost parameters is still missing.

1.3 Research questions

The main goal of this research is finding the answer to the questions below:

1- How can the manufacturing cost of a shell and tube heat exchanger be estimated?
2- Which method of costing is more reasonable for estimation of the manufacturing processes?
3- What is the most suitable optimization method for designing a shell and tube heat exchanger?
4- How can the cost function be generated to estimate the manufacturing cost of shell and tube heat exchangers?

1.4 Framework

In this study, which is a development of a previous study accomplished by Saari et al. (2016) at LUT School of Energy Systems, an analytic generative cost model for manufacturing of shell and tube heat exchangers is introduced and a MATLAB code is written based on the generated cost model as an objective cost function for the optimization process. The Differential Evolution algorithm is utilized for optimization process which provides the cost estimation of the optimum thermal and constructional specifications for the manufacturing process of a shell and tube heat exchanger using two different groups of decision variables. In chapter two various types of heat exchangers are introduced. Chapter 3 outlines the design steps of a shell and tube heat exchanger. The manufacturing cost estimation models are discussed in Chapter 4. The process of generating the objective function for optimization and the Differential Evolution algorithm is introduced in Chapter 5. Chapters 6 to 8 include the results, discussion, and the conclusions of the research.

1.5 Literature review

The design optimization of shell and tube heat exchangers has been investigated widely. A variety of techniques have been utilized for cost, thermal, and hydraulic modeling of the shell and tube heat exchangers to provide the objective function of different optimization methods. Annual cost including investment and operational costs has been considered as the objective function in many studies. For instance, Asadi et al. (2014), implemented Cuckoo Search Algorithm (CSA) to optimize the total annual cost and compared the result to the results of Particle Swarm Optimization (PSO) and Genetic Algorithm (GA) showing 77% and 48% possible reduction in operational cost respectively. Vahdat Azad & Amidpour

(2011), employed constructal theory to design shell and tube heat exchangers to obtain the objective function for GA to optimize the total cost of the heat exchanger. Mizutani et al. (2003), developed a model based on generalized disjunctive programming to determine the heat-exchange design and optimized the total annual cost accounting for area and pumping expenses using the mixed-integer nonlinear programming reformulation. Şencan et al. (2011), employed Artificial Bee Colony (ABC) for minimization of the total cost of the heat exchanger by varying several design variables and gained reduced total cost in various case studies for identical operational parameters.

Minimum equipment cost has also been the objective of several studies which consider the heat transfer area as the governing parameter of the equipment cost. Chaudhuri et al. (1997), used Simulated Annealing (SA) algorithm which was coupled by HTRI (Heat Transfer Research, Incorporation) design program to run an iterative optimization procedure and showed that SA algorithm can achieve an optimal solution with 5% of error compared to the global optimum and may result in the global optimum in some cases. Selbaş et al. (2006), applied GA for the design optimization of shell and tube heat exchanger by varying several design variables with the objective function of heat transfer area. They concluded that GA is considerably faster than other techniques and can provide multiple solutions with similar quality resulting in more flexibility in the design process. Costa & Queiroz (2008), formulated the design optimization of shell-and-tube heat exchangers proposing an optimization algorithm based on an oriented search along the tube count table aiming minimization of the thermal surface area for a certain service, considering discrete decision variables. They tested the performance of the algorithm in two case studies and showed the capability of their approach to gain more effective designs than literature. Babu & Munawar (2007), employed Deferential Evolution (DE) for the first time to find the minimum heat transfer area of shell and tube heat exchanger. They explored different strategies of DE for a case study and compared the performance of DE and GA for a similar problem and concluded that DE is considerably faster than GA and delivers the global optimum for a broad variety of design variables.

There have been some unusual optimization objectives considered by previous researchers; Guo et al. (2009), considered minimization of dimensionless entropy generation rate as the objective function and applied GA to obtain the solution of the optimization problem. Patel

& Rao (2010), considered minimization of difference between tube side and shell side heat transfer coefficients as an objective function to compare the sensitivity of PSO and GA approaches. Özçelik (2007), focused on minimization of the aggregate of the annual capital cost and exergetic cost of the shell and tube heat exchangers as an objective function to be optimized by GA.

Furthermore, the optimization of shell and tube heat exchanger is considered as a multi-objective optimization problem in some literature. The minimization of annualized cost and the amount of cooling water required was selected as the objective function by Agarwal & Gupta (2008). Hilbert et al. (2006), also tackled the issue as a multi-objective problem and applied GA to maximize the heat transfer rate while minimizing the pressure drop in a tube bank heat exchanger. Liu & Cheng (2008), optimized a recuperator to maximize heat transfer effectiveness and minimize exchanger weight and pressure loss simultaneously. Also, Sanaye & Hajabdollahi (2010) considered maximization of effectiveness and minimization of the total cost as two objective functions for the optimization of shell and tube heat exchangers.

2 HEAT EXCHANGERS

Heat exchangers are heat transfer equipment in which two or more fluids with different temperatures exchange their internal thermal energy. In most heat exchangers, a solid wall separates the fluids and they are not in direct heat conduction and not mixed ideally. Heat exchangers are used in a wide range of applications like process, power generation, refrigeration, chemical and petrochemical industries, air conditioning, transportation, dairy, food industries and so on. (Thulukkanam, 2013, p.57.) They might be known by several names regarding their heat transfer functions such as radiators, regenerators, evaporators, reboilers, condensers (Singh & Soler, 1984, p.1). Heat exchangers have several classifications but regarding construction, tubular heat exchangers such as double pipe, shell and tube, and spiral tube in addition to plate heat exchangers like brazed, welded, spiral and so on, are the most common types of them (Thulukkanam, 2013, p.58).

2.1 Types of Heat Exchangers

According to Thulukkanam (2013, p.57), “industrial heat exchangers have been classified according to (1) construction, (2) transfer processes, (3) degrees of surface compactness, (4) flow arrangements, (5) pass arrangements, (6) phase of the process fluids, and (7) heat transfer mechanisms.” Classification of heat exchangers regarding construction includes four main types as follows:

2.1.1 Tubular heat exchangers

Tubular heat exchangers are mostly built of circular or in some applications elliptical, rectangular, or round/flat twisted tubes. Ease of variation of geometry through different diameter, length, and arrangement of tubes provides high range of flexibility in the design. They can be designed for high operating pressure and for fluids with a high difference in pressure. In addition to liquid-to-liquid and liquid-to double phase (evaporation or condensation), they can be utilized for heat transfer between gases and liquids or even gas-to-gas applications in case of high pressure and/or temperature, high rate of fouling, or when no other types are applicable. They might be categorized as shell and tube, double pipe, and spiral tube heat exchangers. (Shah & Sekulic, 2003, p.13.) As this study is focused on shell and tube heat exchangers, they are introduced in section 2.2 more comprehensively.

2.1.2 Plate-type heat exchangers

Plate-type heat exchangers are normally created by thin plates with either smooth or wavy surface. They are not suitable for very high pressure and/or temperature applications in general and are classified as welded, gasketed (as shown in Figure 1) or brazed in accordance with leakage protection demands. (Shah & Sekulic, 2003, p.22.)

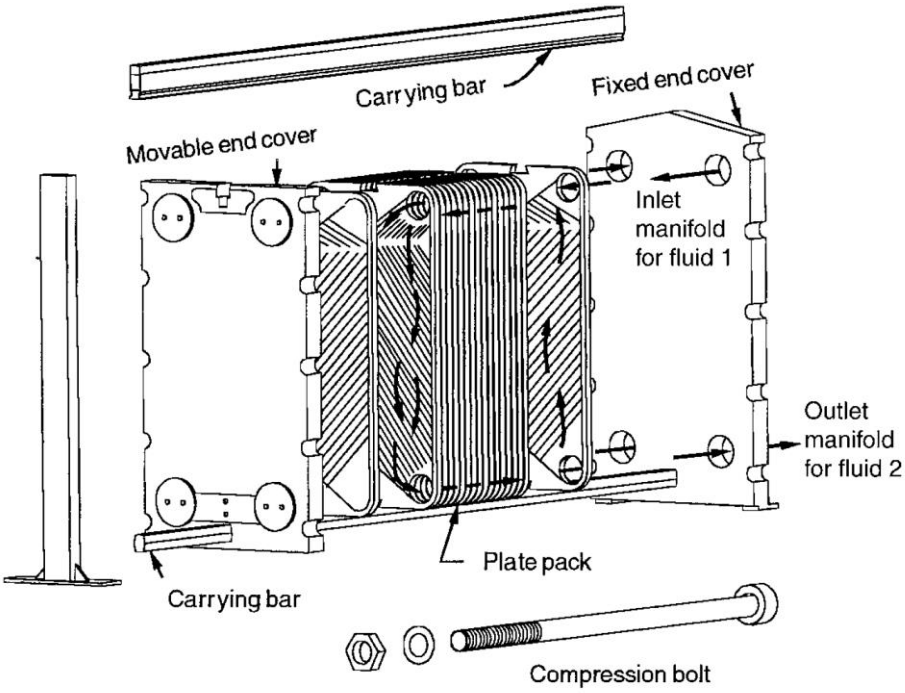

Figure 1. Gasketed plate-and-frame heat exchanger (Shah & Sekulic, 2003, p.23).

2.1.3 Extended surface heat exchangers

Increasing the heat transfer surface area is the most common approach when high effectiveness and compactness of heat exchanger is required, or heat transfer is quite low due to the presence of gases as fluid on one or both sides. It is done by adding extended surface or fins with highest possible fin density. The surface area can be increased by 5 to 12 times the basic surface in accordance with the design. This kind of heat exchangers are called extended surface exchangers and most typical types of them are tube-fin and plate-fin geometries. (Shah & Sekulic, 2003, p.36.)

2.1.4 Regenerative heat exchangers

Regenerative heat exchangers are storage-type heat exchangers in which the heat transfer surface or components are normally called as a matrix. They operate either by periodic movement inward or outward of the steady flow of gases (rotary regenerators as shown in Figure 2) or the flow of gases are directed into or out of fixed matrices (fixed matrix regenerators). (Shah & Sekulic, 2003, p.47.)

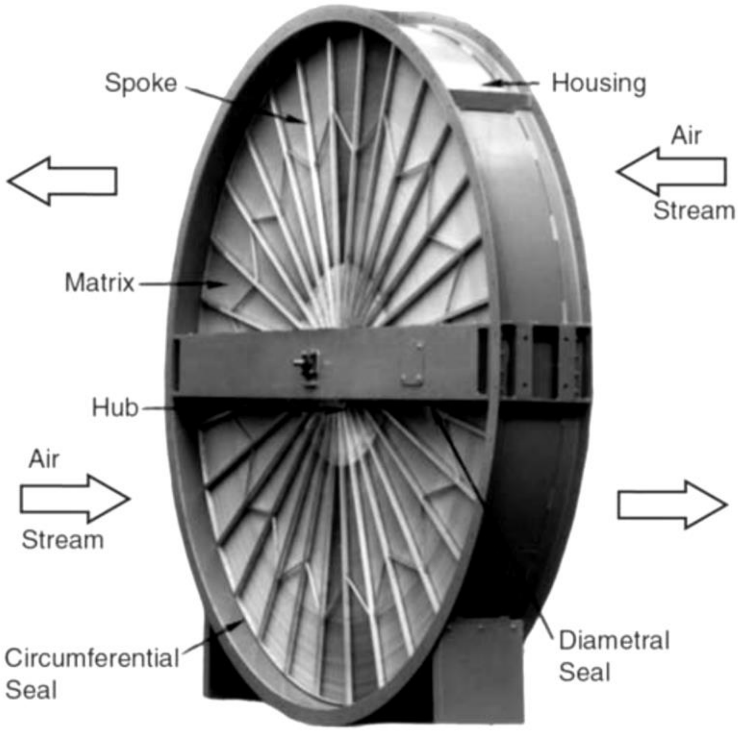

Figure 2. Rotary regenerator or heat wheel made from a polyester film (Shah & Sekulic, 2003, p.48).

2.2 Shell and tube heat exchangers

Shell and tube heat exchangers are normally constructed of a bundle of tubes installed in a cylindrical shell with the same axis of the tube bundle. Tube wall separates the fluids and transmits thermal energy between them. They include more than 90% of heat exchangers used in process industries and are produced in many different sizes and classes. There is almost no limitation for their operating pressure and temperature. (Shah & Sekulic, 2003, p.13; Thulukkanam, 2013, p.64.) A typical shell and tube heat exchanger is shown in Figure 3.

The initial design of shell and tube heat exchangers was innovated more than 100 years ago to accommodate the needs for oversized heat exchanger surface area in addition to the capability of operation in high pressure as condensers and pre-heaters in power plants. They are still utilized in these applications, but their design has become extremely complex and specialized regarding the variation of duties and standards. They were highly used in appearing oil industry as condensers, reboilers, oil heater and cooler for various crude oil elements and other organic fluids in severe operating conditions. (Schlünder, 1983, p.3.3.1_1.)

In early stages of the development of shell and tube heat exchangers, the major problems were about material strength calculations of different components. There was also another sort of problems regarding the manufacturing methods like joining of tube and tube sheet, welding of nozzle and flange, and so on, which many of them are still an area of concern. (Schlünder, 1983, p.3.3.1_1.)

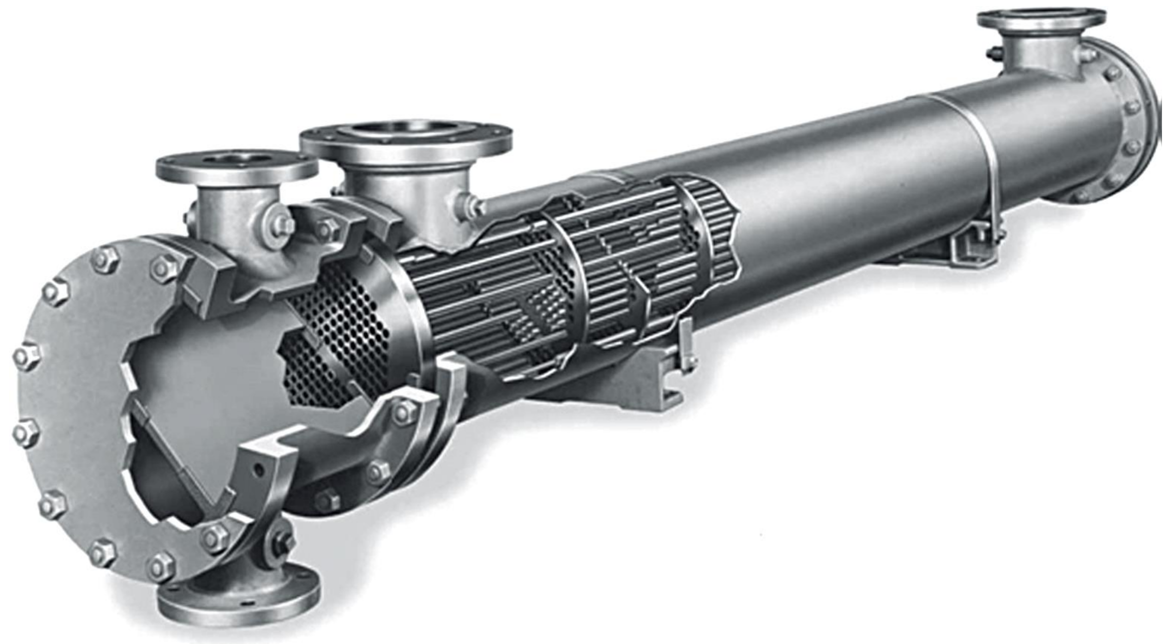

Figure 3. Cut section of a typical shell and tube heat exchanger (Thulukkanam, 2013, p.294).

A Shell and tube heat exchanger has several components in which the main ones are shell, tube bundle, front heat, rear head, baffles, and nozzles. Another important part is expansion joint that might be used in a fixed tube sheet exchanger design. Various internal constructions for shell and tube heat exchangers are used based on required pressure drop and heat transfer performance in addition to leakage, corrosion, cleaning, maximum temperature and pressure, and flow turbulence considerations. (Shah & Sekulic, 2003, p.13.)

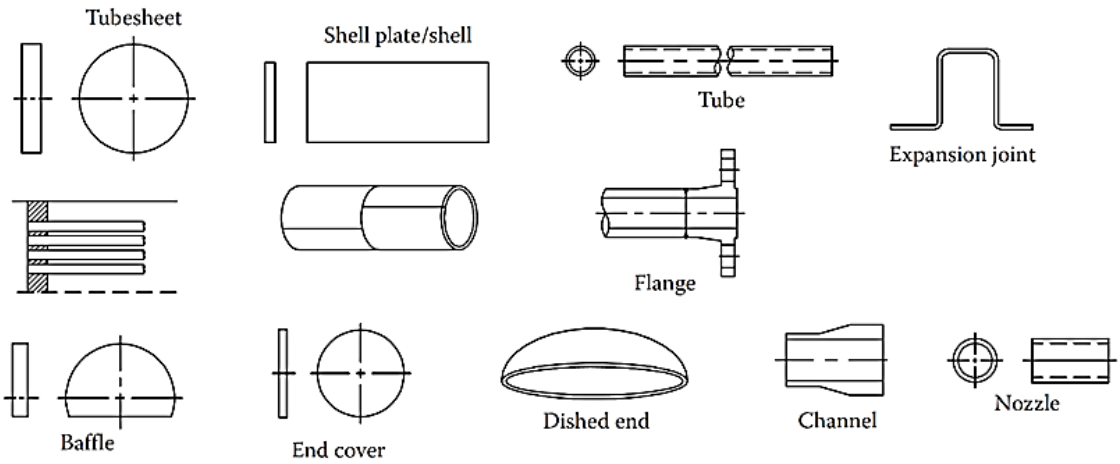

Figure 4. Main components of a shell and tube heat exchanger (Thulukkanam, 2013, p.204).

Classification and construction of shell and tube heat exchangers are performed complying with TEMA (Tubular Exchanger Manufacturers Association) standards and ASME (American Society of Mechanical Engineers) boiler and pressure vessel codes. Other standards like DIN (Deutsches Institut für Normung), BS (British Standards), ISO (International Standards Organization) in addition to other national standards are used by different manufacturers. (Shah & Sekulic, 2003, p.13; Schlünder, 1983, p.4.3.1_1.)

Shell and tube heat exchangers are classified by TEMA in three classes regarding their operational condition as below (Escoe, 1995, p.104):

- Class R: are designed with the highest safety considerations and can operate in highly severe conditions. They are mostly used in oil industries and chemical processes.
- Class C: are designed to operate in moderate conditions. The compact design and economic consideration are necessary attributes of this class of heat exchangers.
- Class B: includes exchangers used for general processes which are designed with the highest compactness and lowest cost for purchasers.

TEMA has also introduced a system of nomination to distinguish most common types of shell and tube heat exchangers in which each exchanger is determined by three letters showing front head, shell type, and rear head respectively; for instance, AES, AEP, BEM, CFU, and so on. The complete set of these different types is indicated in Figure 5. It should be mentioned that other exclusive designs of shell and tube heat exchangers are commercially available which their front and rear heads are different from TEMA standard types and therefore are not referable by this determination system. (Shah & Sekulic, 2003, p.13.)

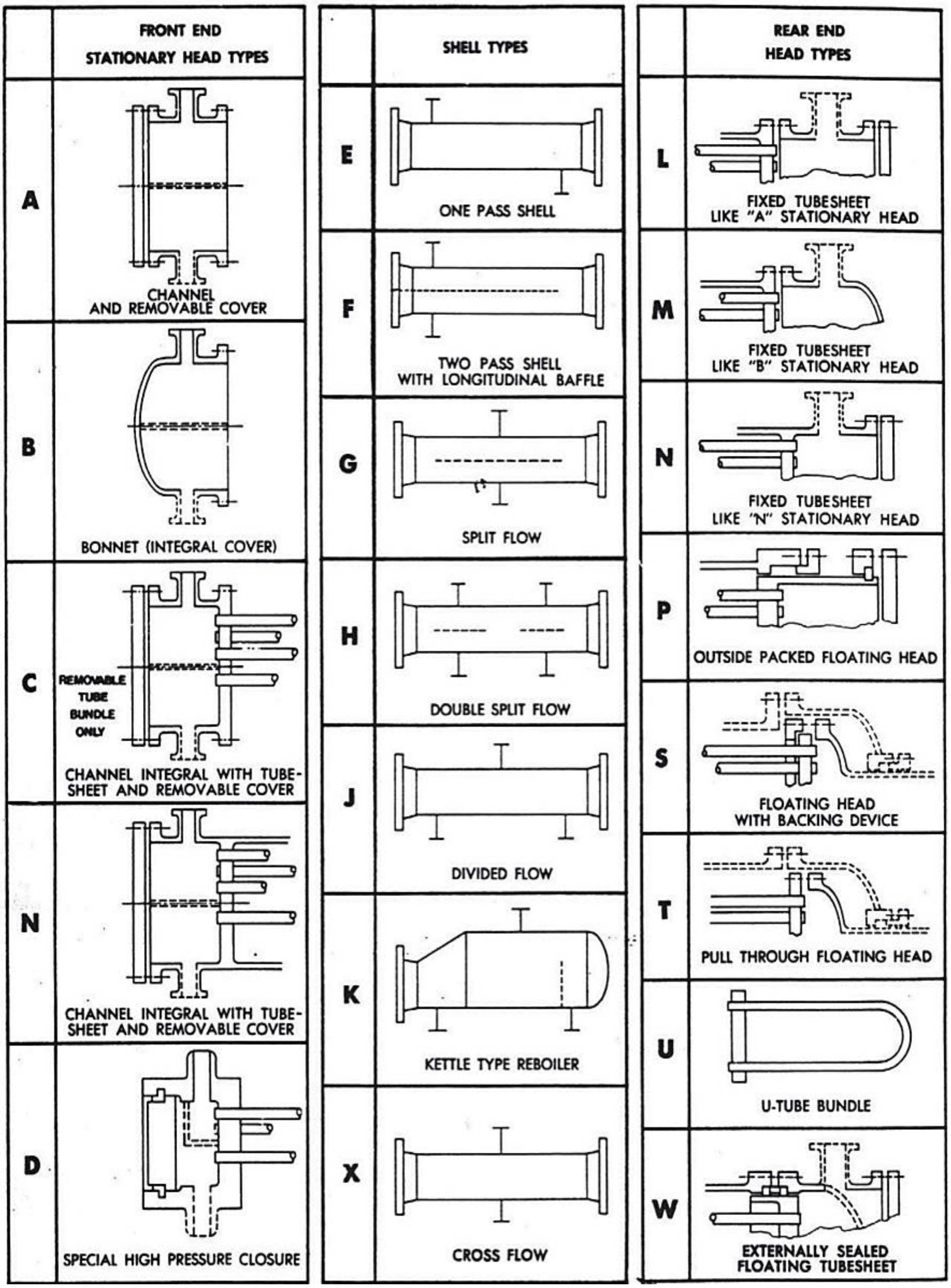

Figure 5. Standard naming system of shell and tube heat exchangers (TEMA, 2007, p.1.2).

2.2.1 Shell

The shells are normally closed cylinders manufactured in a wide range of standard sizes and thicknesses using a variety of materials. To manufacture the shells of smaller sizes, standard size pipes can be used while rolled plates are used to fabricate the larger shells. It is known that designing the heat exchanger with a smaller diameter and the longest length allowed by the plant layout, installation and maintenance limitations delivers more economically efficient heat exchanger. Sometimes, up to six shells with shorter length are arranged in series which operate like one long individual shell. TEMA has specified the nominal shell diameter and thickness as listed in Table 1. The inner side of the shell needs to be round and smooth to avoid fluid bypass from extra space between the baffle edges and shell surface which reduces the performance of the heat exchanger. (Thulukkanam, 2013, p.314.)

Table 1. Nominal shell diameter and thickness (Mod. TEMA, 2007, p.5.3.1).

	Nominal Shell Diameter (mm)	Minimum Thickness (mm)		
		Carbon Steel		Alloy*
		Pipe	Plate	
R-3.13	152	SCH.40	.	3.2
	203-305	SCH.30	.	3.2
	330-737	SCH. STD	9.5	4.8
	762-991	-	11.1	6.4
	1016-1524	-	12.7	7.9
	1549-2032	-	12.7	7.9
	2057-2540	-	12.7	9.5
CB-3.13	152	SCH.40	-	3.2
	203-205	SCH. 30	.	3.2
	330-584	SCH. 20	7.9	3.2
	610-737	.	7.9	4.8
	762-991	-	9.5	6.4
	1016-1524	-	11.1	6.4
	1549-2032	-	12.7	7.9
	2057-2540	-	12.7	9.5

*Schedule 5s is permissible for 152 mm and 203 mm shell diameters.

2.2.2 Tubes

The geometrical parameters of the tubes, like the tube outside diameter, thickness, pitch, and layout patterns are important. They affect the performance of the heat exchanger because the required heat transfer takes place through the tube wall. Circular tubes are widely used in shell and tube heat exchangers. Tubes must tolerate the pressure and temperature range during the operation in addition to the thermal stresses caused by different thermal expansion of the tube bundle and the shell. Also, the tubes must be able to endure contacting corrosive fluids from both inner and outer sides. There are various types of tubes like plain, finned, duplex (bimetallic), and enhanced surface tubes to be used in the exchangers. Another classification considers the tubes as straight tubes and U-tubes. (Thulukkanam, 2013, p.294.)

Shell and tube heat exchangers may have several numbers of tube passes depending on the acceptable pressure drop in the tube side. The number of tube passes may vary from 1 to 10. When more than one pass is required, normally an even number is selected to avoid the thermal and mechanical issues of an odd number of passes. (Shah & Sekulic, 2003, p.681.)

2.2.3 Baffles

The role of baffles is to direct the shell side fluid in the required flow pattern in addition to maintaining the tube spacing and supporting the tubes to avoid vibrations and noises. Baffles are generally categorized as either transverse (normal to the tube bundle) or longitudinal (parallel to the tube bundle). Except for K and X shell types which have only plates to support the tube bundle, the other types of shell and tube heat exchanger have transverse baffles. The most common type of the transverse baffles employed in the shell and tube heat exchangers is the segmental baffle which is a round plate with a removed segment. (Thulukkanam, 2013, p.299.) A common arrangement of segmental baffles is depicted in Figure 6 schematically.

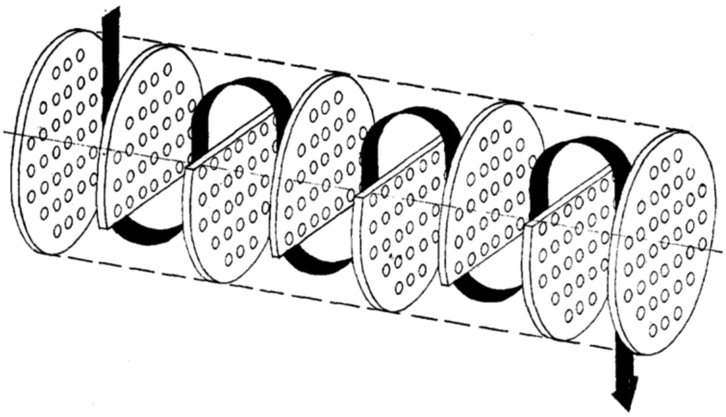

Figure 6. Segmental baffles (Gram, 1960, p.470).

2.2.4 Tube sheet

An important part of a heat exchanger is the tube sheet which separates the shell side and tube side fluids. Appropriate design of the tube sheet is critical to obtain a safe and reliable heat exchanger. Most of the tube sheets are circular in which the tube holes are uniformly drilled as shown in Figure 7. Tube sheets can be welded to the shell and the channel which are referred as an integral type or can be joined to the shell and the channel using flanges and bolts which are called gasketed joints. (Thulukkanam, 2013, p.308.)

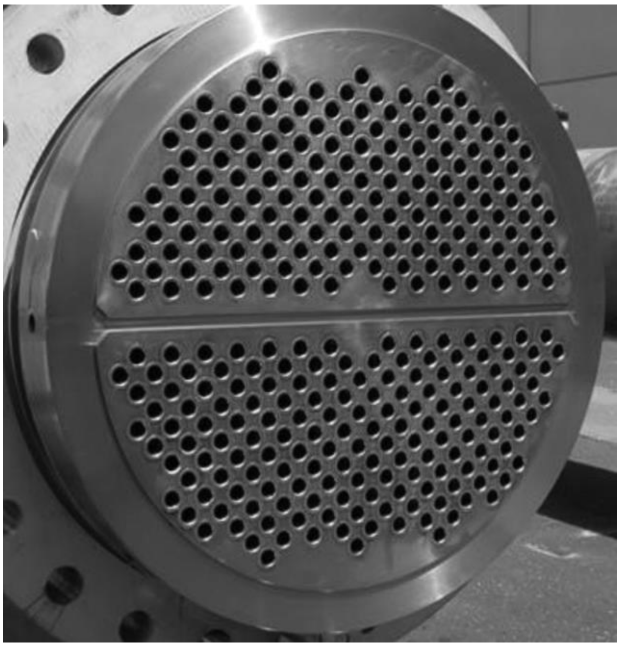

Figure 7. Tube sheet made from titanium (Thulukkanam, 2013, p.309).

2.2.5 Tube layout and pitch

The tubes can be arranged in different patterns and angles relative to the flow direction. The standard tube layouts are triangular and square types which might be oriented in different angles as shown in Figure 8. The tube pitch is the ratio of ligament and tube diameter which is recommended to be in the range of 1.25 to 2.00 by TEMA (2007). The ligament is the length of the tube sheet material between two neighboring holes of the tube sheet as noted by (LGM) in Figure 8. (Shah & Sekulic, 2003, p.681.)

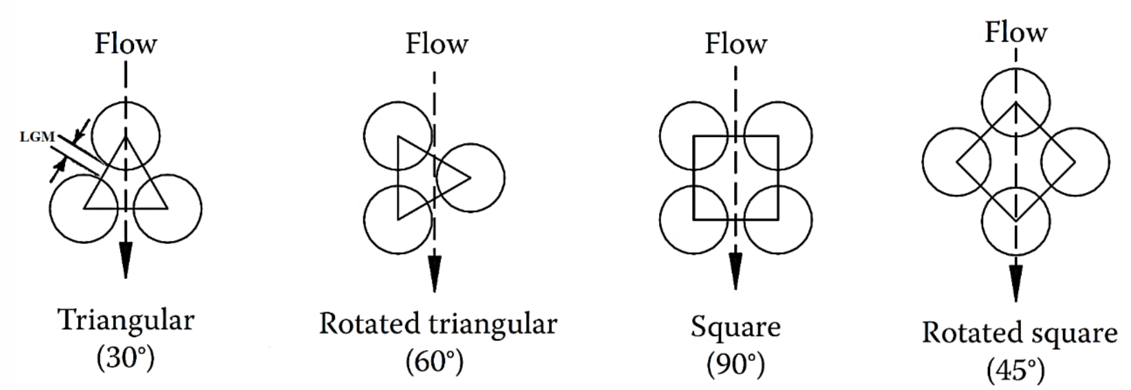

Figure 8. Tube layouts and pitch ratio (Mod. Thulukkanam, 2013, p.295).

2.2.6 End channels

The role of channels is to distribute the tube side fluid into the tubes properly. Pass plates are installed inside the channels of multi-pass heat exchangers to separate the fluids in different tube passes. The channel covers are made in various shapes like flat plates or spherical end covers. The tube side nozzles are connected to the channels which let the tube side fluid enter and exit the tubes. (HEI, 2012, p.3.)

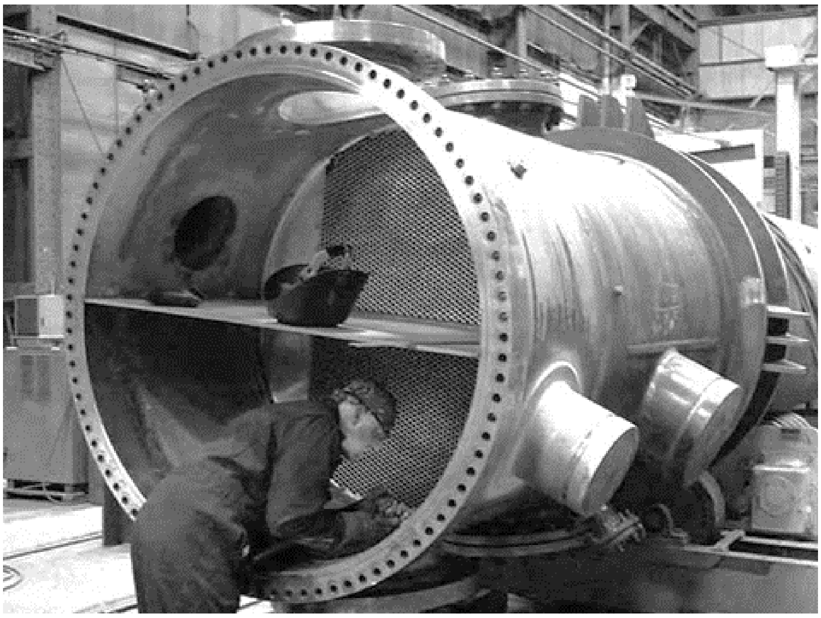

Figure 9. End channel of a shell and tube heat exchanger (Joseph Oat Corporation, 2012).

3 DESIGN STEPS OF SHELL AND TUBE HEAT EXCHANGERS

Several factors should be considered in the design process of shell and tube heat exchangers to achieve a reliable design which can satisfy the application requirements optimally. The general design procedure of heat exchangers which is shown in Figure 11 includes (Thulukkanam, 2013, p.173):

- Determination of the process characteristics
- Thermohydraulic calculations to guarantee the heat transfer capacity and meet the pressure drop limitation necessity
- Consideration of the vibrations caused by both shell side and tube side flows
- Mechanical design based on the standards and codes and compatible to the operating situation and conditions
- Manufacturing limitations and desired cost range
- Compromise parameters and optimization of overall system performance

3.1 Thermohydraulic design

The thermohydraulic design problem of a heat exchanger has two categories regarded as rating and sizing. The rating means to specify the heat transfer capacity and pressure losses of flows for an existing exchanger or an exchanger with determined sizes. An effective rating method of shell and tube heat exchangers is the Bell-Delaware method. The fundamental program of the Bell-Delaware method is presented in Figure 10. The sizing problem deals with the geometrical specifications of the heat exchanger. The sizing problem includes determining the type of the exchanger construction, selecting the proper arrangement of shell side and tube side flows, material selection, and dimensioning of both sides. (Thulukkanam, 2013, p.177.)

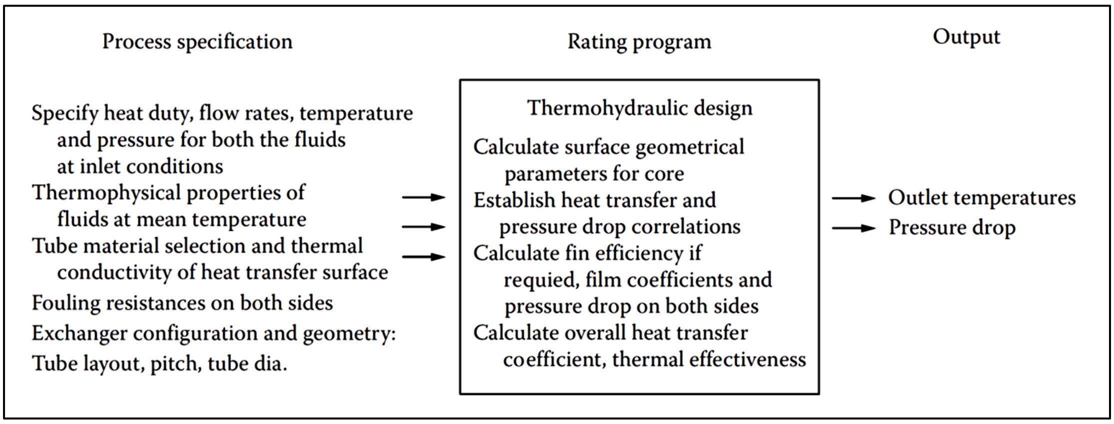

Figure 10. Fundamental program of Bell-Delaware method (Thulukkanam, 2013, p.177).

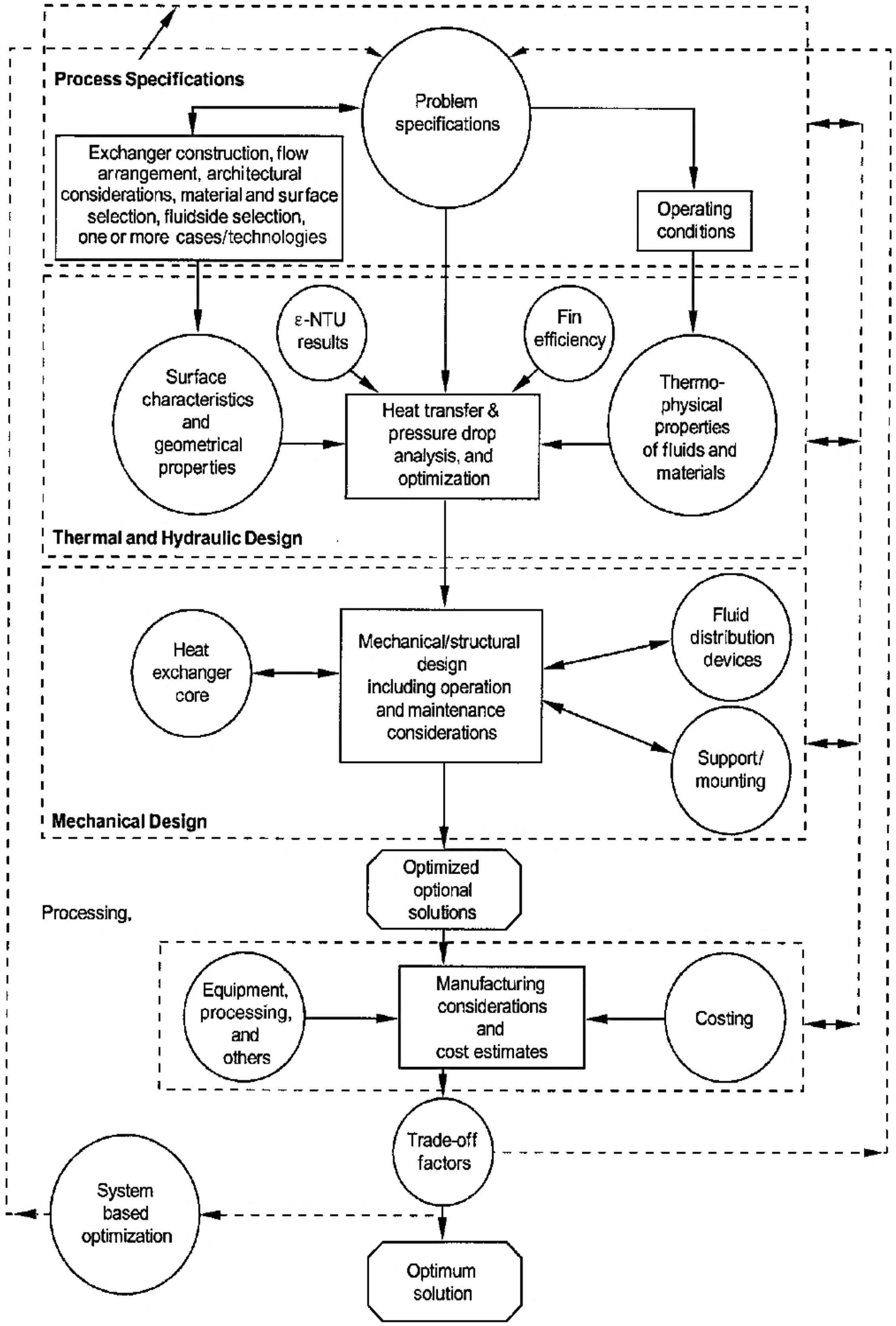

Figure 11. Design procedure of heat exchangers (Shah & Sekulic, 2003, p.80).

The first requirement to solve the sizing problem of a shell and tube heat exchanger is the determination of the thermal effectiveness. Various methods are introduced to estimate the thermal effectiveness like Number of Transfer Units (NTU) methods (ε-NTU, P-NTU_t) Logarithmic Mean Temperature Difference (LMTD) method, and ψ-P method. (Thulukkanam, 2013, p.98.)

3.1.1 ε-NTU method

To obtain the required surface area of a heat exchanger using the ε-NTU method, firstly the exchanger effectiveness (ε) is calculated using given inlet and outlet temperatures and then the heat capacity rate ratio (C^*) is computed. Then NTU is determined using known ε, C^*, and specified charts according to the direction of the flows. Finally, the area needed for the heat transfer duty is obtained as (Thulukkanam, 2013, p.179.):

$$A = \frac{(NTU)c_{min}}{U} \tag{1}$$

Where U is overall heat transfer coefficient and c_{min} represents smaller heat capacity rate of the fluids. As an example, an ε-NTU chart for unmixed crossflow exchanger is shown in Figure 12.

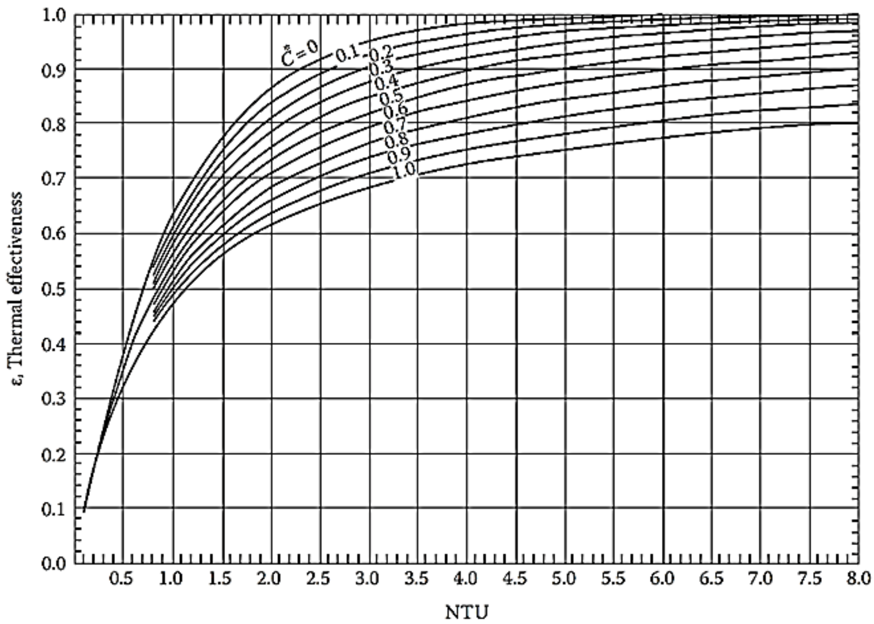

Figure 12. ε-NTU chart for unmixed crossflow heat exchanger (Thulukkanam, 2013, p.107).

3.1.2 LMTD method

To estimate the required surface area of a heat exchanger using the LMTD method, firstly the thermal effectiveness (P) and heat capacity ratio of tube and shell fluids (R) are computed based on given inlet and outlet temperatures. In the next level the correction factor (F) is determined by F-P charts using known (P) and (R) and according to the direction of the flows. An example of the F-P charts is shown in Figure 13 for TEMA E type of shell. Then the required heat transfer surface area is estimated as (Thulukkanam, 2013, p.179.):

$$A = \frac{q}{[UF(LMTD)]} \tag{2}$$

In which (q) is the overall heat transfer rate and the LMTD is computed according to the known inlet and outlet temperatures.

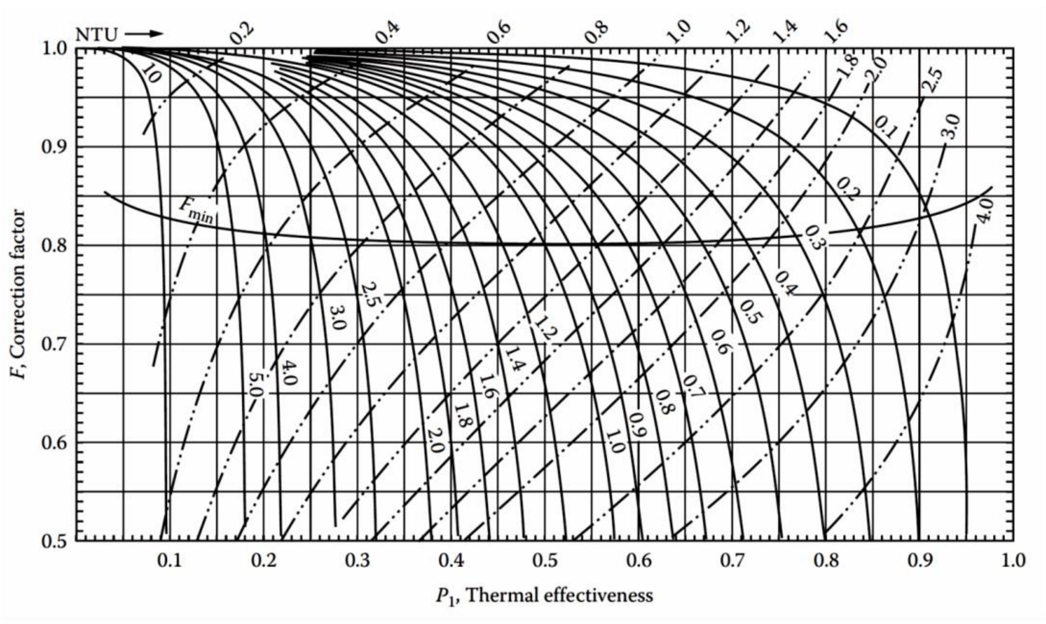

Figure 13. F-P chart for TEMA E type of shell (Thulukkanam, 2013, p.133).

3.2 Mechanical design

Heat exchangers are expected to endure a variety of loads and stay functional under severe operational conditions. To ensure the reliability of the service and functionality of shell and tube heat exchangers, mechanical design criteria are introduced as specified construction procedure in several codes and standards. (Thulukkanam, 2013, p.630.) The international design codes which are broadly used to perform the mechanical design of heat exchangers are listed in Table 2.

Table 2. International design codes for mechanical design of heat exchangers (Mod. Thulukkanam, 2013, p.623).

Code Name	Country
ASME Code, Section III, Section VIII, Divs. 1 and 2	The United States
PD 5500	The United Kingdom
CODAP	France
AD Merkblatter 2000	Germany
UPV Code EN 13445	Europe
ANNC	Italy
Stoomwezen	Dutch
ISO/DIS-2694	International
IS:2825-1969	India
GOST	USSR
Pressure Vessel Code (Dai Isshu Atsuryouk Youki Kousou Kikahu)	Japan
Regels voor Toetsellen Onder Druck	The Netherlands

One of the most used design standards for the mechanical design of shell and tube heat exchangers is TEMA standards which briefly introduced in Section 2.2. TEMA standards are applicable for the design of shell and tube heat exchangers in a limited range of specifications. The scope of TEMA standards is indicated in Table 3.

Table 3. Scope of TEMA standards (Mod. Thulukkanam, 2013, p.621).

Parameter	Limit
Inside diameter	60 in. (1524 mm)
Nominal diameter × pressure	60,000 lb/in. (10,500 N/mm)
Pressure	3,000 psi (20,670 kPa)
Shell wall thickness	2 in. (50.8 mm)
Stud diameters (approx.)	3 in. (76.2 mm)
Construction code	ASME Section VIII, Div. 1
Pressure source	Indirect (unfired units only)

The most important components of a shell and tube heat exchanger which must be considered in the mechanical design procedure are as follows (Thulukkanam, 2013, p.631):

1- The thickness of the shell
2- The design of flanges for the shell and the channel
3- The calculation of the channel endplates either dished or flat
4- The type and joining method of nozzles
5- The thickness of tube sheet
6- The longitudinal and bending stresses for the shell, tubes, and channels
7- The load applied to the joint of tubes to the tube sheet
8- The supports to keep the equipment in place
9- Cost of manufacturing and materials

A typical order to proceed with a robust mechanical design for shell and tube heat exchangers is suggested as follows (Thulukkanam, 2013, p.633):

1- Characterize affecting loads
2- Specify suitable codes and relevant standards
3- Choose the material to construct different parts
4- Calculate the thickness and strength of under-pressure parts
5- Choose the suitable welding process and characteristics
6- Ensure to comply with all thermohydraulic conditions
7- Design the characteristics of the part which are not under pressure
8- Choose suitable checking and inspection method

To perform the abovementioned design procedure, a designer can follow two different approaches which are classified as “design-by-rule” and “design-by-analysis”. In the first approach, the detailed calculation and analysis of all stresses are not required, and a set of equations based on the previous successful experiences can be used for dimensioning of the most commonly used parts. The second approach requires the analysis of all the stresses based on specific criteria. Further details regarding the mechanical design procedure of heat exchangers including all the formulations and required considerations are demonstrated by Singh & Soler (1984), and Thulukkanam (2013).

4 MANUFACTURING COST OF SHELL AND TUBE HEAT EXCHANGERS

4.1 Manufacturing cost estimation methods

Manufacturing cost can be estimated using a variety of methods according to the type of available information. The classification of methods is pointed as intuitive methods, parametric approaches, variant-based models, and generative cost estimation. Variant-based costing where estimation is based on similar formerly manufactured products, and generative cost estimation where detailed manufacturing operations are specified, are the main methods for manufacturing cost estimation. Intuitive methods are based on the experience of estimators and have individual nature. Parametric methods relate characteristic parameters of the product to manufacturing cost using statistical approaches. (Xu et al., 2012, p.302.)

The total cost of an engineering product includes many different elements which are paid by the manufacturer to provide raw materials, machines and parts, processing and delivering the final product to the customer. The total cost can be categorized as direct and indirect costs. Direct costs are those which can be directly assigned to the generation of a particular product consisting the cost of material, labor, machine tools, and so on, which are used in the manufacturing process. Indirect costs are those which are normally combined and assigned to a set of products produced in a particular interval, often referred as overhead costs. It consists distribution costs, inspection and supervision costs, in addition to indirect material costs such as lubricants and so on. Different components of a product total cost are shown in Figure 14. (Adithan, 2007, p.102.)

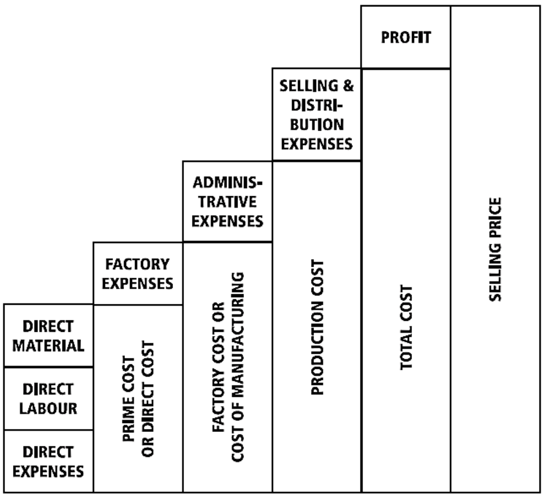

Figure 14. Components of a product total cost (Adithan, 2007, p.106).

4.2 Costing model for shell and tube heat exchangers

Most of the available cost formulations for heat exchangers use variant-based costing or parametric methods to estimate the manufacturing cost. This appears to be the result of relatively simple and systematized structure or their broad usage in process industries and chemical engineering where parametric methods are developed and have been used effectively. Nevertheless, the accuracy range of these models is usually reported between 10% to 30%. The fundamental parameter of heat exchangers cost estimation formulas is the heat transfer area which indicates the size of the exchanger. Simple cost formulations based on the heat transfer area of a heat exchanger were developed by Hall. He has arranged the cost equations for different structures and materials of heat exchangers. (Caputo et al., 2016, p.515.)

As an example, parametric cost formulation for carbon steel is introduced as

$$C_{FOB} = 30800 + 750\ A^{0.81} \tag{3}$$

In which C_{FOB} is the capital investment ($), showing the Free on Board (FOB) cost also known as direct manufacturing cost and A is the surface area (m^2) (Hall et al., 1990, p.324).

To increase the accuracy of parametric methods, some application and structure coefficients can be multiplied by the initial surface area estimation. This method is a combination of parametric, statistical, and variant-based models (Caputo et al., 2016, p.515.) For instance, the basic cost estimation of a standard specification of the heat exchanger (material: carbon steel, internal pressure: less than 690 kPa, exchanger type: floating head, heat transfer area: among 13$m^2$and 1114m^2) is calculated as

$$C_{bas} = e^{[8.551 - 0.30863 \ln(A) + 0.06811\ (\ln(A))^2]} \tag{4}$$

Then the cost estimation for actual specification of the heat exchanger is computed as

$$C_{FOB} = F_{typ} F_p\ F_{mat} C_{bas} \tag{5}$$

In which, F_{typ} is the exchanger type correction factor, F_p is the actual operating pressure correction factor, and F_M represents the correction factor for the construction materials. (Corripio et al., 1995, p.126.)

There are further improvements of combined parametric, statistical, and variant-based approach like the Purohit method which can be considered as one of the most sophisticated and detailed costing methods for heat exchangers until now, with lower than ±15% of error margin. More details of Purohit method are available in (Purohit, 1982). Another method is considering the relation of the exchanger cost to its weight, as:

$$C_{FOB} = e^{\alpha + \beta \, ln(W_{HE})} \tag{6}$$

Where α and β are specified coefficients according to the type and material of equipment and W_{HE} represents the weight of heat exchanger. (Shabani & B. Yekta, 2006, p.28; Caputo et al., 2016, p.516.)

4.2.1 Deficiencies of statistical, variant-based, and parametric costing methods

Although the above-mentioned approaches are used in a wide range of applications, they do not provide accurate cost estimation in a detailed design process due to following reasons (Caputo et al., 2016, p.516):

- They are based on a specific case or are made by statistical data related to a specific structure which may differ from the required features for the heat exchanger to be designed.
- Manufacturing related variables or the details of geometrical architectures are not included in the correlations explicitly. Therefore, they cannot respond to the changes of design variables when, for instance, the heat transfer area or the weight of the equipment is maintained.
- Instead of manufacturing cost, they rather deliver purchasing cost which is affected by market situations.
- They are only applicable in a limited range of size; for example, Hall’s formulations are implemented to the heat transfer areas lower than $140m^2$.
- The high error margin of statistical cost models leads to the incapability of comparison between various structures of the equipment or small dimension differences.

- There is a possibility that no model is available for a specific material category or operating situation.
- The error margin of such models increases after few years due to inflation and alteration of the market situation. They need to be escalated by employing cost indices to account these sorts of changes. Despite, cost indices do not reflect the changes in manufacturing techniques and technical modifications.

Parametric cost models are not comprehensive enough to be used in numerical optimization methods or for computer-aided design processes since the selected structure by the algorithm might differ from the standard specification which the parametric model is based on, or design changes implemented by the algorithm might not be reflected by the objective cost function. This is more problematic when the basis of the objective cost functions are extremely simplified cost formulations like Hall's formulas. This problem becomes obvious when the same heat transfer area and different construction is considered. (Caputo et al., 2016, p.517.)

4.2.2 Generative cost estimation model

According to the deficiencies of parametric models mentioned in the previous section, generative cost estimation models are preferable due to having considerable advantages such as (Caputo et al., 2016, p.517):

- Ability to reflect the effect of design variations on the manufacturing cost.
- Delivering up-to-date cost estimation regardless of the cost indices if the material, manufacturing process, and labor costs are provided.
- Updating them to consider technology improvements and changes in manufacturing operations or raw material prices is achievable easily.
- Sensitivity to changes in the details of selected construction and geometrical specification by the designer even if the whole equipment size is maintained similar to the previous design.
- No validity limitation for selecting the sizes over the normal range, which was a matter of concern in parametric models.

Accordingly, to obtain a detailed manufacturing cost estimation model which reflects the actual specifications of manufacturing processes and constructive features, a generative cost estimation model for shell and tube heat exchangers will be introduced in the following section. It should be mentioned that the introduced costing model is not an alternative to the widely used parametric model because they consider the market price and this model accounts the manufacturing process cost. Hence, the results of these two approaches are not comparable. (Caputo et al., 2016, p.517.)

The introduced model is based on the model developed by Caputo et al. (2016) and some minor adjustments are applied to make it compatible with the focused construction and increase the details considered regarding the cost of different processes. The focused TEMA type of their model was AEL while the BEM TEMA type (as shown in Figure 5) is considered here due to the lower manufacturing cost of its end channels. The model is formulated according to the general process plan to produce fixed tube-sheet heat exchangers introduced by Thulukkanam (2013) and estimation formulas are taken from Creese et al. (1992).

The direct manufacturing cost of heat exchangers can be calculated as the sum of materials and processes cost using formulas below (Caputo et al., 2016, p.518):

$$C_{FOB} = \sum\nolimits_{x} C_{m,x} \tag{7}$$

Where, $C_{m,x}$ is the direct manufacturing cost of x^{th} component of the equipment.

To make a simpler cost model, some costly nonsignificant components such as nozzles and impingement plate are neglected. Also, only major operations are considered in the cost model.

The direct manufacturing cost of components is defined as:

$$C_{m,x} = C_{mat,x} + \sum\nolimits_{k=1}^{N_{op}} C_{op,k} \tag{8}$$

In which, N_{op} is the number of several processes needed for each component and the material cost of x^{th} component is obtained as:

$$C_{mat,x} = V_x \rho_x C_{mat,x} \tag{9}$$

Where V is volume (m^3), ρ is density (kg/m^3) and C_{mat} (€/kg) is the cost of material per weight.

The k^{th} operation cost of x^{th} component is defined as:

$$C_{op,k} = \left(\frac{L_k}{v_k}\right) C_{H,k} \tag{10}$$

Considering L as the processing length (m), v as the velocity (m/h) and C_H as the hourly cost of operation (€/h).

A more detailed hourly cost of processing can be calculated as the sum of labor, equipment amortization and energy, and other consumables cost as below:

$$C_{H,k} = C_{H,L,k} + C_{H,amo,k} + C_{H,EN,k} \tag{11}$$

In which $C_{H,amo,k}$ is the amortization cost computed as:

$$C_{H,amo,k} = I_k . \frac{\tau_k}{awh} \tag{12}$$

Where τ is the capital recovery factor, I is the capital investment and awh is annual working hours.

The labor cost is defined as:

$$C_{H,L,k} = LR.m \tag{13}$$

Where LR is the labor rate (€/h) and m shows the number of workers involved in the process.

Finally, Hourly energy cost will be:

$$C_{H,EN,k} = P_k . C_{el} + C_{H,ANC,k} \quad (14)$$

In which P (kW) is the used power, C_{el} the energy cost (€/kWh) and $C_{H,ANC,k}$ is the hourly cost of other consumed and ancillary materials.

4.2.3 Cost of the manufacturing operations

To keep the model simpler, the manufacturing operations cost is only based on the duration of each main operation and fixed costs and subsidiary operation are not considered; since they are fixed by definition and do not affect the result of the optimization procedure. To estimate the manufacturing cost of a shell and tube heat exchanger, the required manufacturing processes for each major part of the equipment should be specified. Various operations to make the major parts of a shell and tube heat exchanger are listed in Table 4.

There are a variety of technologies to manufacture the shell of a heat exchanger depending on the geometrical specifications. When the diameter of the shell is less than 0.6 m, commonly, a seamless tube can be utilized, while for larger diameters, the shell is made by rolling and welding of metal plates. The two variations need different manufacturing processes and the cost of manufacturing is higher for the rolled plate option. (Caputo et al., 2016, p.518.) The manufacturing processes for the shell is shown in Figure 15. The tube-sheets are welded to the shell after installation of the tube bundle.

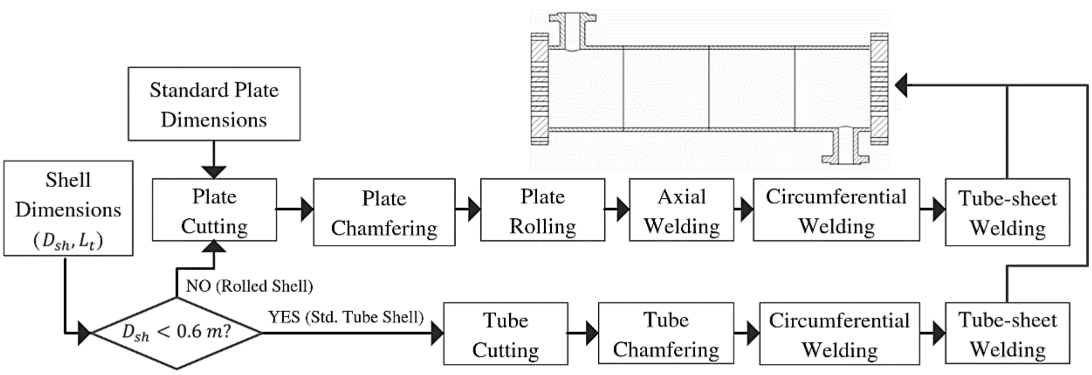

Figure 15. Shell manufacturing process diagram (Mod. Caputo et al., 2016, p.517).

Table 4. Major parts of shell and tube heat exchanger and their manufacturing processes (Mod. Caputo et al., 2016, p.518).

Component	Process
Shell	
- Made from tube (Ds<0.6)	
	Cutting
	Chamfering
	Circumferential welding
	Tube sheet welding
- Made from plate	
	Cutting
	Chamfering
	Rolling
	Welding of longitudinal seams
	Circumferential welding
	Tube sheet welding
Tube-sheet	
	Cutting
	Edge beveling
	Drilling
Baffle	
	Cutting
	Beveling
	Drilling
Tube	
	Cutting
	Chamfering
	Welding
Channel	
	Same as shell manufacturing, only flange welding will replace the tube-sheet welding
- Tori-spherical end plate	
	Cutting
	Chamfering
	Convexing
	Welding to channel shell
Assembly	Final assembly operations

To produce the shell from commercial seamless tubes, cutting, chamfering, and welding processes are required. The length of the cutting process depends on the ratio between the length of the shell and available standard length of the seamless tubes which is assumed to be 12 meters in this study. The number of required seamless tubes would be:

$$N_{shtb} = sup.int.\left(\frac{L_{sh}}{L_{StdTb}}\right) \tag{15}$$

Where, the term $sup.int.$ means the supremum integer of the obtained fraction.

The cutting length of seamless tubes in cases where $\frac{L_s}{L_{Std\,Tb}}$ is not an integer, can be estimated as:

$$L_{c,shtb} = \pi D_{sh,avg} \tag{16}$$

Where $D_{sh,avg}$ represents the average diameter of the shell.

The length of the chamfering process can be calculated as:

$$L_{ch,shtb} = 2\ N_{shtb}\ \pi\ D_{sh,avg} \tag{17}$$

The length of welding process to join seamless tubes to each other in cases the length of the shell is longer than one standard tube would be:

$$L_{w,shtb} = (N_{shtb} -\ 1)\ \pi\ D_{sh,avg} \tag{18}$$

If the diameter of the shell is more than 0.6 m, the shell is manufactured by rolling and welding of rectangular plates. In this case, the cost of the manufacturing process depends on the size and number of plates which are used to produce the shell tube. Since there are various standards for plate sizes and different manufacturers offer customized plate sizes, considering all available commercial plate sizes were not justifiable and only 9 dimensions are assumed as available plate options as listed in Table 5.

Table 5. Assumed standard dimensions of metal plate for shell manufacturing.

Option	1	2	3	4	5	6	7	8	9
Length (m)	12	16	15	12	16	12	12	20	15
Width (m)	3	4	5	6	6	4	5	6	7

The length of the cutting process depends on the ratio of the shell dimensions to standard plate dimensions. If the shell size is equal to plate dimensions, then no cutting process is required. When the shell size is larger than available plates, more than one plate is needed and the best available plate considering lowest amount of waste and minimum number of required plates can be selected using the comparison of the side area of the shell and the area of the available plates as below (Abbasi & Sahir, 2010):

$$\frac{A_{plt}}{A_{sh}} = \min\left(\left(\frac{L_{plt}.W_{plt}}{L_{sh}.W_{sh}}\right) \& \left(\frac{L_{plt}}{L_{sh}}.\frac{W_{plt}}{W_{sh}}\right) \& \left(\frac{L_{plt}}{W_{sh}}.\frac{W_{plt}}{L_{sh}}\right)\right) \tag{19}$$

$$N_{shp} = sup.int\left(\frac{A_p}{A_{sh}}\right) \tag{20}$$

Where N_{shp} is the number of required plates, A_{plt} shows the area of standard plate, A_{sh} is the side area of the shell, L and W represent the respective length and width.

The length of the cutting process would be:

$$L_{c,shp} = \pi D_{sh,avg} + L_{sh} \tag{21}$$

The length of the chamfering process is equal to the cutting length. The length of the welding process which depends on the results of comparison between shell dimensions and the standard plate dimensions is calculated as below:

$$L_{w,shp} = L_{sh}N_{shp} + \pi D_{sh,avg}(N_{shp} - 1) \tag{22}$$

The length of the rolling process is calculated as:

$$L_{r,shp} = \pi D_{sh,avg}N_{shp} \tag{23}$$

In this design, tube sheets are welded to the shell after installing the tube bundle and later the channels are welded to tube sheets. The length of welding in this process is calculated as:

$$L_{w,ts} = 4\,\pi\,D_{sh,avg} \tag{24}$$

The manufacturing process of tube sheets is shown in Figure 16. The length of tube sheets cutting and beveling process would be:

$$L_{b,ts} = L_{c,ts} = 2\pi D_{ts} \tag{25}$$

Where, D_{ts} represents the diameter of the tube sheets.

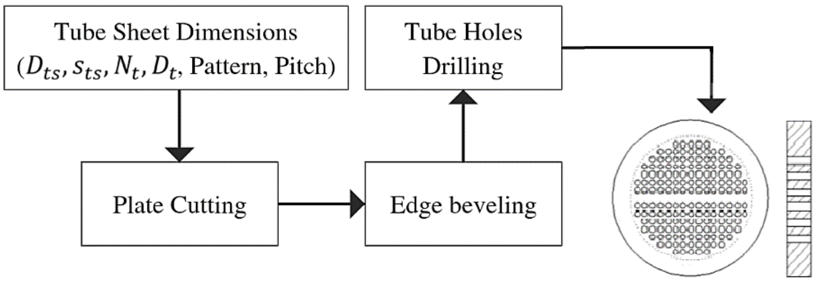

Figure 16. Tube-sheet manufacturing process diagram (Mod. Caputo et al., 2016, p.519).

Tube sheets need to be drilled to keep the tubes inside the drilled holes. The length of tube sheet drilling process would be:

$$L_{d,ts} = 2\, s_{ts} N_{tp} N_{tpp} \tag{26}$$

In which, s_{ts} is the thickness of each tube sheet, N_{tp} shows the number of tube passes, and N_{tpp} is the number of tubes per pass.

The baffles type is segmental which their manufacturing process is depicted in Figure 17.

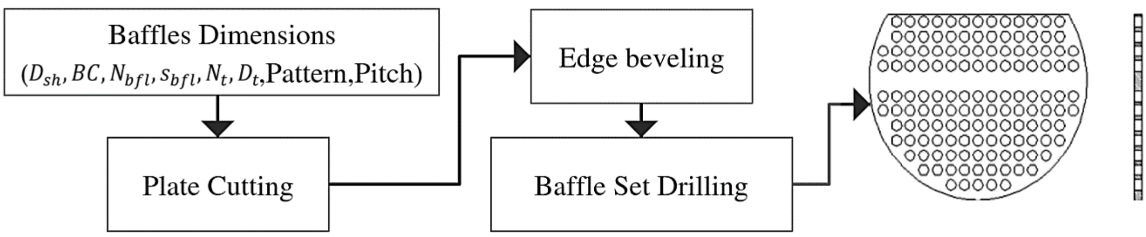

Figure 17. Baffle manufacturing process diagram (Mod. Caputo et al., 2016, p.519).

Baffles are assumed to be cut from rectangular plates with similar standard sizes of plates used for the shell manufacturing part listed in Table 5. The length of cutting and beveling process to manufacture the baffles is calculated as below (Verfahrenstechnik & Chemieingenieurwesen, 2010, p.738; Caputo et al., 2016, p.530):

$$L_{c,bfl} = L_{b,bfl} = (2\pi - (2\cos^{-1}(1 - \frac{2H}{D_{bfl}})))\frac{D_{bfl}}{2} + 2\sqrt{H(D_{bfl} - H)} \qquad (27)$$

Where H is the height of baffle cut as shown in Figure 18.

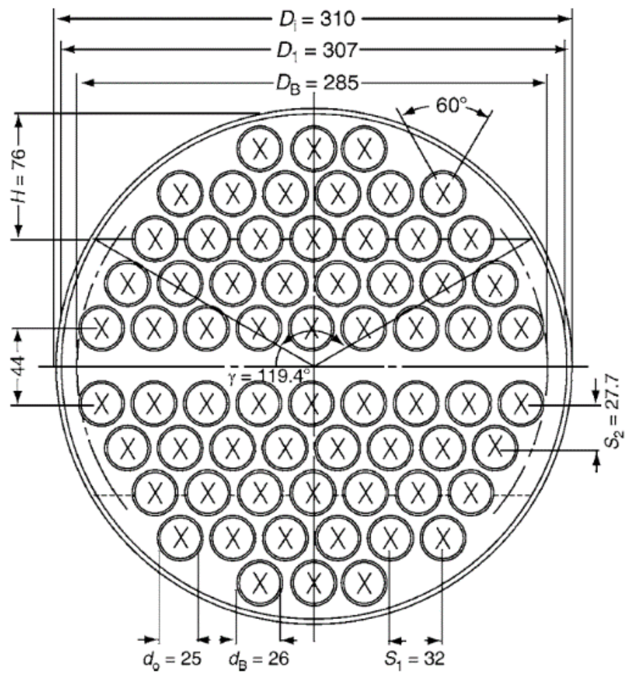

Figure 18. Example of baffle dimensions (Verfahrenstechnik & Chemieingenieurwesen, 2010, p.738).

The drilling process is done in a single pass by clumping all the baffles to each other. The total drilling length of baffle manufacturing process is:

$$L_{d,bfl} = N_{bfl} N_{hol,bfl} s_{bfl} \qquad (28)$$

Where, N_{bfl} is the number of baffles, $N_{hol,bfl}$is the number of holes per baffle, and s_{bfl} represents the thickness of baffles.

The tube bundle can be assembled either outside or inside the shell. Assembling the tube bundle inside the shell is more common due to the simplicity of moving lighter parts instead of the heavy tube bundle. The whole assembly process time is correlated to the time of passing a tube through one hole of baffles. (Caputo et al., 2016, p.519.) In cases that the length of tubes is longer than available standard tubes which are assumed to be 12 meters in this study, chamfering and welding processes are required in addition to the cutting process to prepare the tubes to be assembled in the tube bundle as depicted in Figure 19.

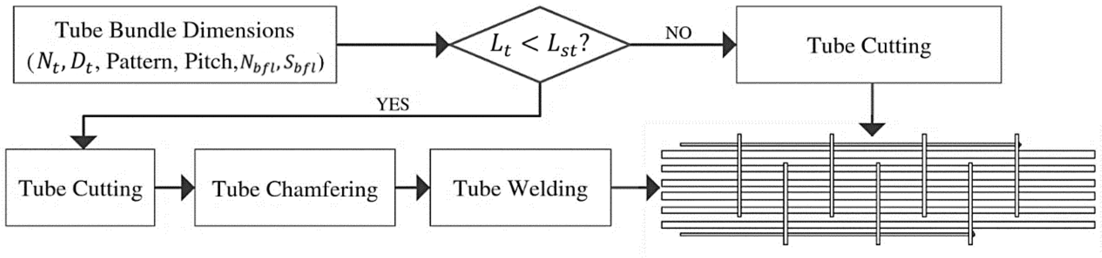

Figure 19. Tube bundle manufacturing process diagram (Mod. Caputo et al., 2016, p.519).

The length of tube cutting process is calculated as:

$$L_{c,t} = \begin{cases} N_t \pi D_{t,o} & if \ \frac{L_t}{L_{st}} \neq integer \\ 0 & otherwise \end{cases} \tag{29}$$

In which, N_t is the number of tubes, $D_{t,o}$ is the outside diameter of tubes, L_t is the length of tubes, and L_{st} represents the length of available standard tubes.

The length of tube chamfering and welding process in cases that the length of required tubes is longer than standard tubes would be:

$$L_{ch,t} = L_{w,t} = N_t \pi D_{t,o} \left(sup.int \left(\frac{L_t}{L_{st}} \right) - 1 \right) \tag{30}$$

Channel type ends are used for the BEM TEMA type heat exchangers. The process of channel manufacturing is mostly similar to the shell manufacturing process with the differences in length and having the torispherical dished end plate. The channel manufacturing process is illustrated in Figure 20.

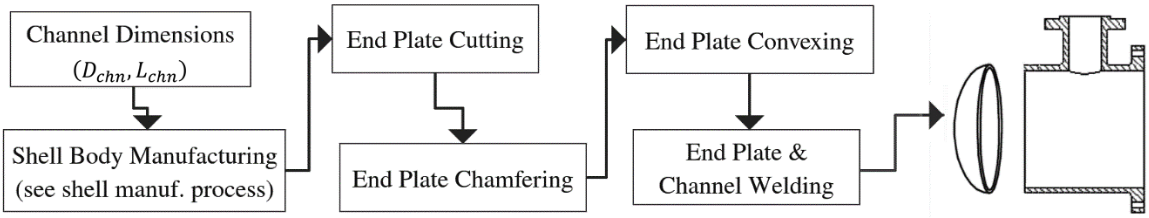

Figure 20. Channel manufacturing process diagram (Mod. Caputo et al., 2016, p.519).

Instead of the length of the process, exceptionally, the area of the convexing process is considered to estimate the manufacturing cost of the torispherical dished end plate. The blank area of the plate used to produce each torispherical dished end plate can be calculated as:

$$A_{dshnd,chn} = 1.69 \, \frac{\pi}{4} \, D_{chn,in}{}^{2} \tag{31}$$

Where, $D_{chn,in}$ is the inside diameter of channels. The coefficient of 1.69 is an experimental estimation for the ratio of the surface area of torispherical end palate to its projected area (efunda, 2009).

The length of welding process to join two torispherical end palates to the channels would be:

$$L_{w,chn} = 2 \, \pi \, D_{chn,avg} \tag{32}$$

Where, $D_{chn,avg}$ represents the average diameter of the channel.

The cost of above-mentioned processes is calculated using the Equation (8). For the welding and rolling process, a cost per length and for the convexing process of the channel heads, a cost per area is used instead of the hourly cost of the process. Due to lack of availability of accurate and valid data for the cost of various manufacturing processes and the speed of operations, the cost and the speed of processes are initially assumed as listed in Table 6 considering the values used by Caputo et al. (2016), and then the selected assumptions are varied in the range of 50% to 150% of the initial values to evaluate their effect on the results of the optimization procedure and perform a sensitivity analysis.

Table 6. Cost and speed assumptions of processes.

Variable	Value	Variable	Value
Shell plate cutting	100 €/h	Beveling (chamfering)	60 €/h
Shell tube cutting	90 €/h	Rolling	7 €/m
Tube cutting	70 €/h	Channel head Convexing	50 €/m^2
Drilling	80 €/h	Tube bundle assembly	40 €/h
Welding	10 €/m	drilling speed	1 m/min
cutting speed	2 m/min	Beveling speed	5 m/min

4.2.4 Cost of the materials

The cost of materials can be estimated based on the Equation (7) by multiplication of the volume and the density of each component of the shell and tube heat exchanger. The volume of the shell is calculated as below:

$$V_{sh,mat} = \pi\, D_{sh,avg}\, s_{sh} L_{sh} \tag{33}$$

The volume of tube sheet would be:

$$V_{ts,mat} = \frac{\pi}{4}\, {D_{ts}}^2\, s_{ts} N_{ts} \tag{34}$$

Tubes which are used to manufacture the tube bundle will have the volume calculated as:

$$V_{t,mat} = \frac{\pi}{4}\left({D_{t,o}}^2 - {D_{t,in}}^2\right) L_t N_t \tag{35}$$

Where, $D_{t,in}$ represents the inside diameter of the tubes.

To calculate the volume of baffles, the total surface area of a single segmental baffle including the surface area of the tube holes is considered. The total volume of the baffles would be:

$$V_{bfl,mat} = \left((2\pi - \gamma)\frac{\pi}{4}\, {D_{bfl}}^2 + (D_{bfl} - H)\sqrt{H\left(D_{bfl} - H\right)}\right) s_{bfl} N_{bfl} \tag{36}$$

Where γ is the central angle of the baffle cut and calculated as:

$$\gamma = 2\cos^{-1}\left(1 - \frac{2H}{D_{bfl}}\right) \tag{37}$$

In this study, four different materials to manufacture the components of the heat exchanger are considered, which are listed in Table 7, according to the European Standards (EN). The optimization procedure will select the material which delivers the lowest cost of manufacturing.

Table 7. List of materials considered for shell and tube heat exchangers (EN standard) (Breslavsky, 2017).

Grade	Number	Classification	Density
P235GH	1.0345	Non-alloy quality steel	7.85 g/cm ³
X5CrNiMo17-12-2	1.4401	Austenitic stainless steel	8 g/cm ³
X1CrNiMoCuN24-22-8	1.4652	Austenitic stainless steel - special grade	8 g/cm ³
X2CrNiCuN23-4	1.4655	Austenitic-ferritic stainless steel - special grade	7.8 g/cm ³

The introduced cost model can be used for estimation of the manufacturing cost of shell and tube heat exchanger and is not comparable by parametric models which estimate the purchasing price of the equipment. Since the data of real manufacturing costs are considered as confidential information by manufacturers, there is no straightforward method for validating the details of the discussed model while the general structure of the model remains quite beneficial for overall manufacturing cost estimation.

5 OPTIMIZATION BY DIFFERENTIAL EVOLUTION ALGORITHM

In this chapter, the manufacturing cost optimization approach using the Differential Evolution algorithm is described. Two different case studies are selected from the literature and two sets of decision variables are tested to see the effect of discrete and continuous variation of the design parameters on the optimum design of shell and tube heat exchangers.

5.1 Differential Evolution algorithm

Differential Evolution algorithm is a global optimization method derived from the GA which is broadly used in the field of engineering. Firstly, Storn & Price (1997) introduced it as a promising algorithm to obtain the solution of the Chebychev Polynomial fitting problem. At the same year, it appeared as an outstanding optimization algorithm at the First International Contest on Evolutionary Computation in Nagoya. It has been widely utilized for a variety of real-valued objective functions and has proved its effectiveness and reliability through more than 20 years of application. (Li & Liu, 2010, p.V3_153.)

5.1.1 Advantages of the Differential Evolution algorithm

The advantages of the Differential Evolution algorithm can be mentioned as (Li & Liu, 2010, p.V3_153):

1- Showing persistent constancy to optimize nonlinear, multimodal, and nonconvex functions
2- High convergence speed with the same accuracy compared to the other optimization algorithms
3- Strong capability to solve multi-objective optimization problems

5.1.2 Operational steps of the Differential Evolution algorithm

The Differential Evolution performs four steps to deliver the global optimum solution as follows (Price et al., 2005, p.38; Li & Liu, 2010, p.V3_153):

Step 1 – Initialization

In this step, the upper and lower limits of each parameter are defined. Then a random number generator creates a set of n-dimensional vectors by assigning a value within the specified range to all the parameters of each vector. For instance, the value of the jth parameter of the ith vector of the initial population (t=0) is built according to the formula below:

$$x_{i,j}(0) = rnd_j(0,1) \cdot \left(b_{j,U} - b_{j,L}\right) + b_{j,L} \tag{38}$$

In which, $rnd_j(0,1)$ provides an evenly distributed random number between 0 and 1. $b_{j,U}$ and $b_{j,L}$ are the upper and lower limits of the jth parameter respectively.

Step 2 – Mutation

In mutation step, two members of the current generation (x_{l_2} and x_{l_3}, $l_2 \neq l_3$) are randomly chosen to produce the new candidates of vectors. Afterward, the difference of similar parameters in the selected vectors is calculated and multiplied by a scaling factor to mutate $x_{h_1}$and make a new vector of parameter values as:

$$y_{i,j}(t+1) = x_{l_1,j}(t) + \varphi\left(x_{l_2,j}(t) - x_{l_3,j}(t)\right) \tag{39}$$

Where, φ is a positive real number mostly between 0 and 1 used as a scaling coefficient, t is the generation number and $x_{l_2,j}(t) - x_{l_3,j}(t)$ is the differential vector.

Step 3 – Crossover

To increase the diversity of generated vectors for the new trial population and provide a thorough search scheme for differential mutation, the crossover operation is performed as:

$$z_{i,j}(t+1) = \begin{cases} y_{i,j}(t+1) & if\ (rnd_j(0,1) \leq CR\ or\ j = j_{rnd} \\ x_{i,j}(t) & \text{otherwise} \end{cases} \tag{40}$$

In which, $CR \in [0,1]$ is the crossover probability defined by the user to determine fraction of parameters and j_{rnd} is a uniform randomly selected integer.

Step 4 – Selection

In this step, the value of the objective function for the vector $z_i(t+1)$ is compared to the value obtained from vector $x_i(t)$ and new vector of parameters is made as:

$$x_i(t+1) = \begin{cases} z_i(t+1) & if\big(z_{i1}(t+I),\dots,z_{in}(t+I)\big) < f\big(x_{i1}(t),\dots,x_{in}(t)\big) \\ x_i(t) & if\big(z_{i1}(t+I),\dots,z_{in}(t+I)\big) \geq f\big(x_{i1}(t),\dots,x_{in}(t)\big) \end{cases} \quad (41)$$

Steps 2 to 4 will be repeated until the number of iterations reaches the defined maximum limit and the vector, for which the objective function delivers its minimum value, is found. Figure 21 shows the flowchart of the optimization process by Differential Evolution.

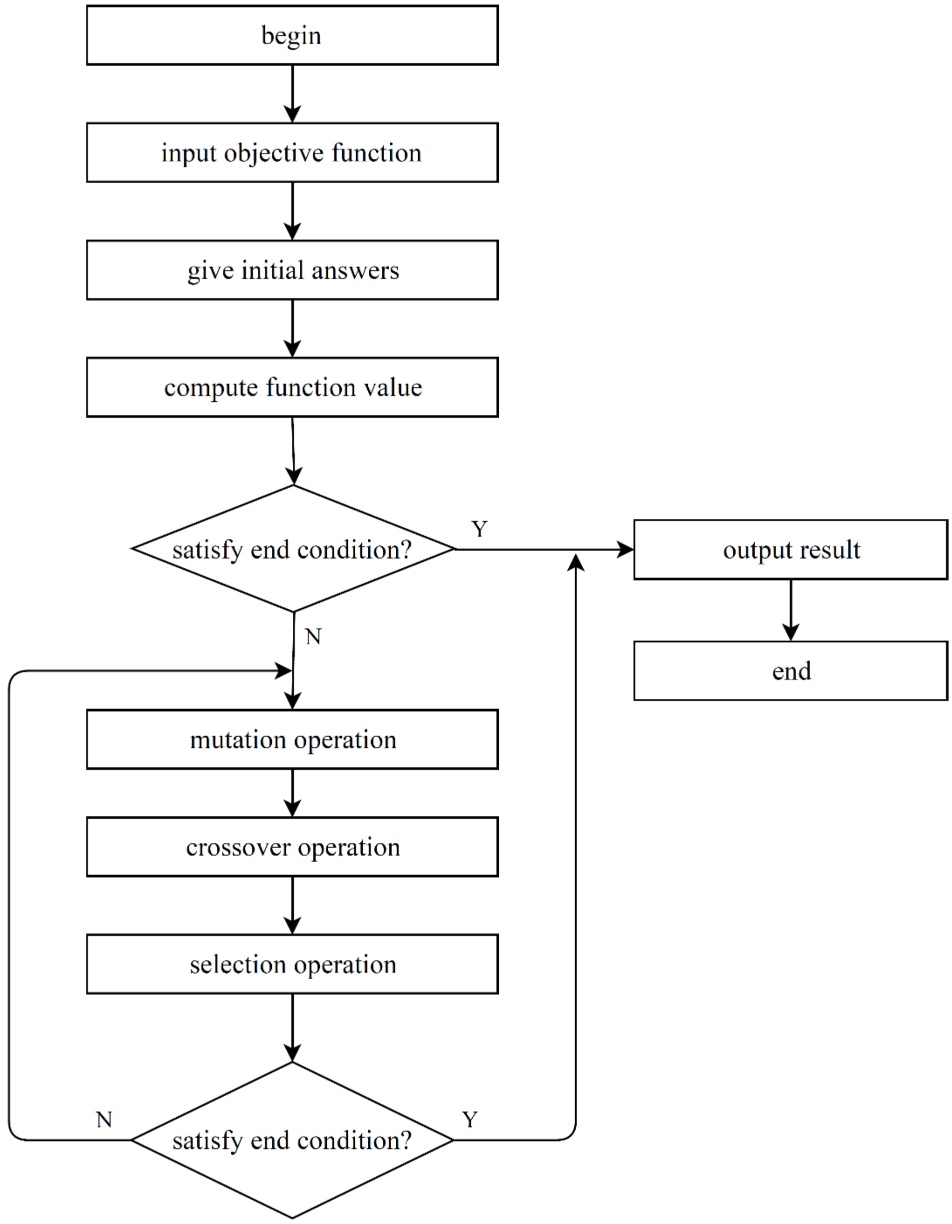

Figure 21. Flowchart of Differential Evolution algorithm (Mod. Li & Liu, 2010, p.V3_154).

5.2 Objective functions

To implement the manufacturing cost optimization procedure using the Differential Evolution algorithm, four objective functions based on the generative cost estimation model (Section 4.2.2) was developed in MATLAB for two case studies and two groups of decision variables. The objective functions used the previously developed codes by Saari et al. (2016) for the thermohydraulic and the mechanical design with minor revisions to guarantee their compatibility with the objective functions. The case studies and the groups of decision variables are referred as (C1, C2) and (D1, D2) respectively. As an example, the developed objective function for the case study 1 and the second group of decision variables (C1-D2) is presented in Appendix II. The Case 1 is taken from (Saari et al., 2016) in which brackish water cools methanol and it is a commonly used example for shell and tube heat exchanger optimization studies. The Case 2 is also used in several optimization studies such as (Asadi et al., 2014; Patel & Rao, 2010; Şencan et al., 2011) in which crude oil is heated by kerosene in an oil refinery preheater. Table 8 represents the specifications of both case studies.

Table 8. Specifications of the case studies.

Case	C1		C2	
heat transfer rate q [MW]	4.34		1.44	
Fluid	Methanol	Brackish water	Kerosene	Crude Oil
Flow rate $\dot{m}$ [kg/s]	27.78	68.88	5.52	18.80
Input/output temperature T_{in}/T_o [°C]	95.0 / 40.0	25.0 / 40.0	199 / 93.3	37.8 / 76.7
Specific heat (isobaric) cp [kJ/kgK]	2.84	4.20	2.47	2.05
Density ρ [kg/m^3]	750	995	850	995
Dynamic viscosity μ [Pa·s]	$3.4 \cdot 10^{-4}$	$8.0 \cdot 10^{-4}$	$4.0 \cdot 10^{-4}$	$3.58 \cdot 10^{-3}$
Thermal conductivity k [W/mK]	0.19	0.59	0.13	0.13
Thermal resistance per surface area R" [m^{2}K/W]	$3.3 \cdot 10^{-4}$	$2.0 \cdot 10^{-4}$	$6.1 \cdot 10^{-4}$	$6.1 \cdot 10^{-4}$

The TEMA type of shell and tube heat exchangers is normally selected based on the operation condition and the fouling characteristics of the fluids. In this study, only the BEM TEMA type (Figure 5), is considered to simplify the optimization process. The selected optimization decision variables and their ranges in both D1 and D2 groups are as listed in Table 9.

Table 9. Optimization decision variables.

Group	Decision variable	Range
D1 & D2	Tube layout, θ [°] #	{30, 45, 60}
	Number of tube passes, N_{tp} [-] #	{1, 2, 4, 6, 8}
	Fluid assignment #	{0, 1}
	Tube outside diameter, $D_{t,o}$(mm) #	{9.52, 12.70, 15.88, 19.05, 22.2, 25.4, 31.8, 38.1, 50.8}
	Baffle cut, BC [%]	15 < BC < 40
	Sealing strip pairs #	{0, 1, …,7}
	Material option #	{0, 1, …,4}
	Shell/Baffle standard plate option #	{0, 1, …,9}
D1	Tube pitch ratio, $LGM/D_{t,o}$ [%]	1.25 ≤ $LGM/D_{t,o}$ ≤ 2
	Baffle-to-shell ratio, S_{bfl}/D_{sh} [-]	0.20 ≤ S_{bfl}/D_{sh} ≤ 1
	Tube-side velocity, v_t [m/s]	0.4 < v_t < 2.5
D2	Tube length, L_t [m] #	{1.219, 1.829, 2.438, 3.048, 3.658, 4.877, 6.096, 7.315}
	Number of tubes per pass, N_{tpp} [-] #	20 ≤ N_{tpp} ≤ 1200
	Number of baffles, N_{bfl} [-] #	{3, 4, …, 25}
	Shell diameter, D_{sh} [m] #	{0.203, 0.254, 0.305, 0.337, 0.387, 0.438, 0.489, 0.540, 0.591, 0.635, 0.686, 0.737, 0.787, 0.838, 0.889, 0.940, 0.991, 1.067, 1.143, 1.219, 1.295, 1.372, 1.448, 1.524}

Discrete variables

The ranges and values of the decision variables are selected according to TEMA (2007). When the cold fluid flows through the tube side, the value of fluid assignment variable is 0 and it is assigned as 1 when the opposite situation occurs. Baffle-to-shell ratio is the ratio of the distance between two neighboring baffles and the shell diameter. The material option value is assigned based on the considered materials listed in Table 7. The Shell/Baffle standard plate option value is assigned according to the Table 5.

5.3 Running the optimizer

The optimization procedure using the Differential Evolution algorithm performed for all objective functions in MATLAB R2017a (academic license) by specifying the controlling values as below:

- Number of population vectors = 130
- Scaling coefficient (φ) = 0.9
- Crossover probability (CR) = 0.9
- Maximum number of iterations = 700

5.4 Variation of cost parameters

As mentioned in the Section 4.2.3, the costs of various manufacturing processes are initially assumed as listed in Table 6 and then the costs are varied in the range of 50% to 150% of the initial assumptions to evaluate their effect on the results of the optimization procedure. This process was done by calling the optimization procedure iteratively for 20 different uniformly distributed values of each assumption in the specified range and the other assumptions were kept constant as their initial value.

6 RESULTS

In this section, the results of the design and cost optimization procedure in addition to the analysis of the effect of assumed cost parameter values are presented.

6.1 Optimum design and cost values

The results of the optimization procedure include the optimum dimensions of the major components of the heat exchanger in addition to the estimated cost of manufacturing processes and required materials for the specified optimum design. The optimum specifications of both case studies with two different groups of decision variables which are listed in Table 10 are obtained using the initial assumption values of the manufacturing cost parameters as described in Section 4.2.3.

Table 10. Results of the optimization procedure.

Parameter	Symbol	Unit	C1-D1	C1-D2	C2-D1	C2-D2
Shell diameter	D_{sh}	[mm]	530	520	460	469
Shell thickness	s_{sh}	[mm]	10	10	10	10
Tube bundle diameter	D_{otl}	[mm]	517	507	447	456
Baffle cut	BC	[%]	29	35	35	37
Number of baffles	N_{bfl}	[–]	16	15	10	7
Baffle spacing	S_{bfl}	[mm]	457	451	305	456
Tubes external diameter	$D_{t,o}$	[mm]	19	16	16	16
Tubes internal diameter	$D_{t,in}$	[mm]	15.2	12.8	12.4	12.6
Tubes pitch	LGM	[mm]	24.8	21.0	20.0	21.3
Tube pitch ratio	$LGM/D_{t,o}$	[%]	1.30	1.31	1.25	1.33
Tube layout angle	θ	[°]	60	60	60	60
Number of tube passes	N_{tp}	[–]	1	1	6	6
Tubes number	N_t	[–]	343	482	312	282
Tubes length	L_t	[m]	8.34	7.32	3.76	3.66
Tubes effective length	$L_{t,eff}$	[m]	8.13	7.12	3.62	3.52
Length–diameter ratio	L_t/D_{sh}	[–]	15.73	14.07	8.16	7.80
Tube side	–	[–]	Cold fluid	Cold fluid	Hot fluid	Hot fluid
Tube-side flow velocity	v_t	[m/s]	1.04	1.16	1.01	1.11
Shell-side flow velocity	v_{sh}	[m/s]	0.15	0.16	0.13	0.09
Shell-side Prandtl number	Pr_{sh}	[–]	5.08	5.08	5.65	5.65
Tube-side Prandtl number	Pr_t	[-]	5.69	5.69	7.60	7.60
Shell-side heat transfer coefficient (convective)	h_{sh}	[W/m²K]	2708.44	2456.98	959.64	1478.63
Tube-side heat transfer coefficient (convective)	h_t	[W/m²K]	5827.48	6713.41	2402.31	2641.36
Overall heat transfer coefficient	U	[W/m²K]	844.39	823.82	335.12	389.00
Heat exchange area	A	[m²]	166.92	171.09	56.28	49.51
Shell-side pressure drop	Δp_{sh}	[kPa]	26.01	25.76	10.98	5.16
Tube-side pressure drop	Δp_t	[kPa]	10.02	14.53	27.84	33.03
Operating cost	$C_{O,tot}$	[€]	2343.94	2767.48	548.31	440.46
Direct material cost	$C_{mat,tot}$	[€]	7471.19	7822.72	3094.50	2998.89
Direct operation cost	$C_{op,tot}$	[€]	2748.73	2779.12	1754.42	1447.58
Direct manufacturing cost	$C_{m,tot}$	[€]	10219.92	10601.85	4848.92	4446.47
Total manufacturing cost	C_{FOB}	[€]	25345.40	26292.58	12025.32	11027.25
Total life-cycle cost	$C_{FOB} + C_{O,tot}$	[€]	27689.35	29060.06	12573.63	11467.71

6.2 Analysis of the manufacturing cost parameters

The effect of variation of the selected manufacturing cost parameters including:

- The hourly cost of tube bundle assembly
- The hourly cost of beveling
- The hourly cost of drilling
- The hourly cost of plate cutting
- The hourly cost of tube cutting
- Cost of welding per length
- Cost of plate rolling per length
- and Area cost of dished end convexing

on the direct manufacturing cost of shell and tube heat exchanger are indicated as scatter charts for 20 different values for each parameter while the others are kept constant. The resulted scatter charts are sorted in Figure 22 for the case study 1 with the first group of decision variables. The scatter charts for the Case 1 with the second group of decision variables in addition to the charts for the Case 2 are presented in Appendix I.

To compare the effect of each parameter on the direct manufacturing cost, the positive and negative deviation of the costs are calculated based on the trendlines of the scatter charts shown in Figure 22 and the results are listed in Table 11.

Table 11. Deviation of the direct manufacturing cost according to the variation of the cost parameters.

Cost Parameter	Lowest value	Highest value	Range of parameter variation	Deviation of the Direct manufacturing cost
Hourly cost of tube bundle assembly (€/h)	20	60	±50%	±1.939624
Hourly cost of beveling (€/h)	25	75	±50%	±1.158425
Hourly cost of drilling (€/h)	30	90	±50%	±1.148028
Hourly cost of plate cutting (€/h)	50	150	±50%	±2.330175
Hourly cost of tube cutting (€/h)	35	105	±50%	±0.135424
Cost of welding per length (€/m)	5	15	±50%	±2.554907
Cost of plate rolling per length (€/m)	3.5	10.5	±50%	±1.362272
Area cost of dished end convexing (€/m^2)	25	75	±50%	±0.169228

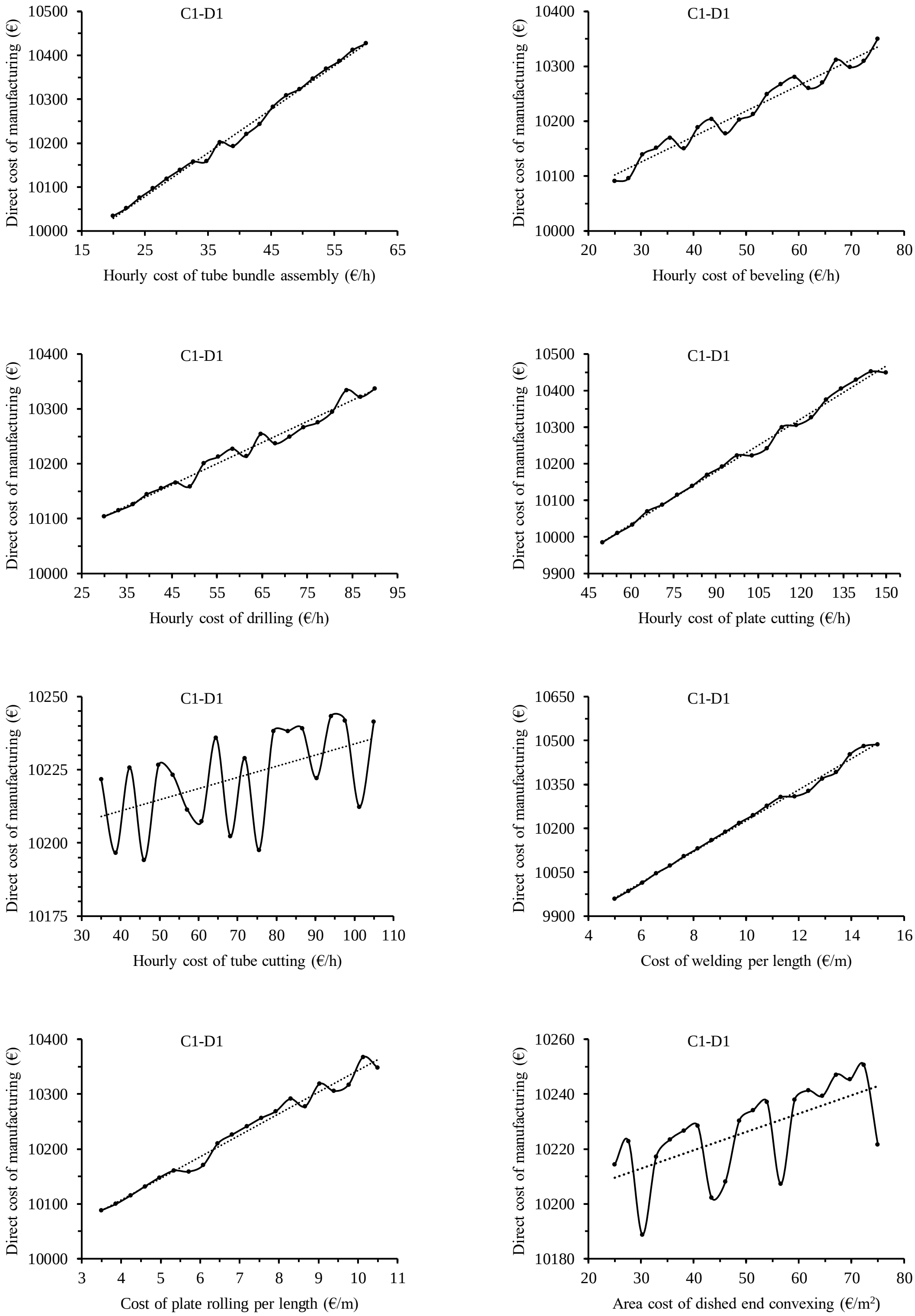

Figure 22. Scatter charts of the effect of manufacturing cost parameters on the direct cost of manufacturing for the case study 1 and the first group of decision variables.

7 DISCUSSION

In this section, the comparison of the optimization results to a previous research, the sensitivity analysis for the manufacturing cost parameters, and the key findings of the research are presented.

7.1 Comparison with a previous research

The selected research for comparison is the study performed by Caputo et al. (2016) since the method of cost estimation used in this study is based on their work and they have used the similar case study as the case study 1 of this research. Table 12 shows their results for optimum shell and tube heat exchanger specifications besides the results of this work for the case study 1 with both groups of decision variables.

Table 12. Comparison of the results of the optimization procedure.

Parameter	Symbol	Unit	Caputo et al. (2016)	This study C1-D1	This study C1-D2
Shell diameter	D_{sh}	[mm]	762	530	520
Shell thickness	s_{sh}	[mm]	11	10	10
Tube bundle diameter	D_{otl}	[mm]	744.8	517	507
Baffle cut	BC	[%]	40	29	35
Number of baffles	N_{bfl}	[–]	9	16	15
Baffle spacing	S_{bfl}	[mm]	700	457	451
Tubes external diameter	$D_{t,o}$	[mm]	1.30	1.30	1.31
Tubes internal diameter	$D_{t,in}$	[mm]	20	19	16
Tubes pitch	LGM	[mm]	16	15.2	12.8
Tube pitch ratio	$LGM/D_{t,o}$	[%]	26	24.8	21.0
Tube layout angle	θ	[°]	90	60	60
Number of tube passes	N_{tp}	[–]	4	1	1
Tubes number	N_t	[–]	546	343	482
Tubes length	L_t	[m]	7.20	8.34	7.32
Tubes effective length	$L_{t,eff}$	[m]	7	8.13	7.12
Length–diameter ratio	L_t/D_{sh}	[–]	9.4	15.73	14.07
Tube side	–	[–]	Hot fluid	Cold fluid	Cold fluid
Tube-side flow velocity	v_t	[m/s]	1.35	1.04	1.16
Shell-side flow velocity	v_{sh}	[m/s]	0.54	0.15	0.16
Shell-side Prandtl number	Pr_{sh}	[–]	5.69	5.08	5.08
Tube-side Prandtl number	Pr_t	[-]	5.08	5.69	5.69
Shell-side heat transfer coefficient (convective)	h_{sh}	[W/m²K]	3484.2	2708.44	2456.98
Tube-side heat transfer coefficient (convective)	h_t	[W/m²K]	3369.6	5827.48	6713.41
Overall heat transfer coefficient	U	[W/m²K]	805.60	844.39	823.82
Heat exchange area	A	[m²]	240.10	166.92	171.09
Shell-side pressure drop	Δp_{sh}	[kPa]	9.71	26.01	25.76
Tube-side pressure drop	Δp_t	[kPa]	39.55	10.02	14.53
Operating cost	$C_{O,tot}$	[€]	6805.93	2343.94	2767.48
Total manufacturing cost	C_{FOB}	[€]	22641.45	25345.40	26292.58
Total life-cycle cost	$C_{FOB} + C_{O,tot}$	[€]	29447.38	27689.35	29060.06

The solution obtained using the first group of decision variables shows 30.45% of the reduction in shell diameter while the tube length is increased about 15.83% compared to the result of Caputo et al. (2016). The number of tubes is 343 while it was obtained as 546 in their design. It means that the cost of the tube bundle assembly process is considerably lower than their design. Also, the overall heat transfer coefficient is increased around 4.82%. Due to the lower operating cost, the total life-cycle cost has lessened about 6%, although the total manufacturing cost is slightly higher than their result.

The second group of decision variables resulted in a slight increase in tube length while showing about 31.76% decrement in the shell diameter. It means that the resulted heat exchanger is more compact than the one obtained by Caputo et al. (2016). The number of tubes was reduced around 11.72% which leads to a slight decrease in the cost of tube bundle assembly. Finally, the total life-cycle cost shows 1.32% of reduction compared to the previous research.

7.2 Sensitivity analysis

The sensitivity analysis is carried out by obtaining the deviation of the direct manufacturing cost due to the variation of one manufacturing cost parameter while the others are kept constant as mentioned in Section 6.2; the results are depicted in Figure 23.

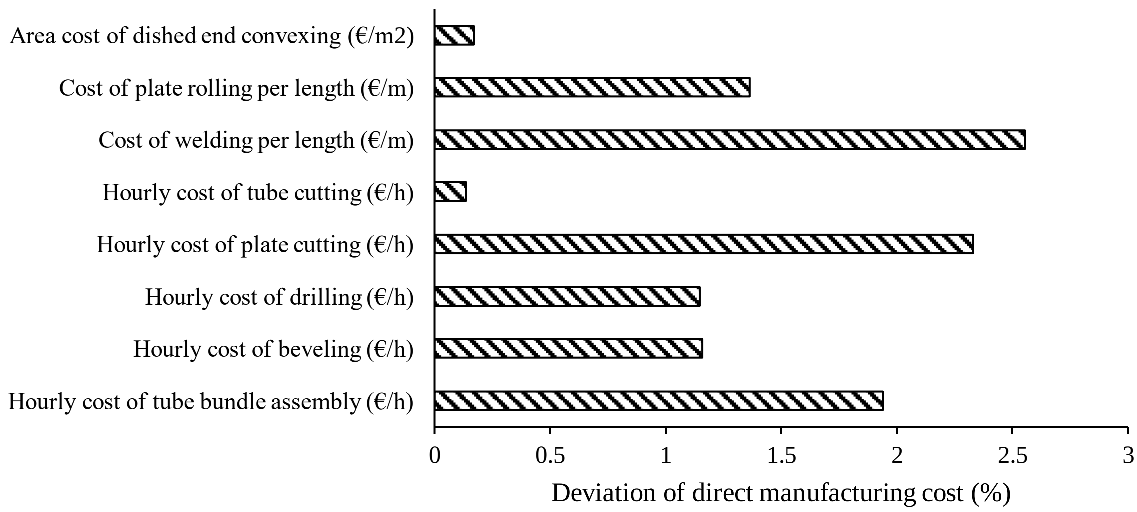

Figure 23. deviation of the direct manufacturing cost due to the variation of manufacturing cost parameters.

The cost of welding process appears to have the highest effect on the direct manufacturing cost while the hourly cost of tube cutting process shows the least effect in this regard. The cost of plate cutting process stays in the second place of the most important parameters.

7.3 Key findings of the research

The considerable points found by this study include:

- To obtain an optimum design of shell and tube heat exchangers which delivers the lowest cost of manufacturing, a detailed costing model including all the manufacturing operations and materials costs is required which considers the effect of any affecting parameter.
- Parametric costing models are not suitable for manufacturing cost optimization purposes since they may stay fixed even if some of geometrical dimensions or manufacturing processes are changed.
- The selection of decision variables has a significant effect on the optimum design specifications.
- Some of the cost parameters appear to have a larger effect on the total manufacturing cost of shell and tube heat exchangers where some others can be neglected.
- Differential Evolution algorithm is a fast and efficient method for optimization of nonlinear, multimodal, and nonconvex problems like the design problem of shell and tube heat exchangers.

8 CONCLUSION

In this study, various types of heat exchangers are described with a focus on shell and tube heat exchangers. The thermohydraulic and mechanical design steps are discussed briefly and then, an analytical generative cost model is introduced for estimation of the manufacturing cost of a shell and tube heat exchangers. Based on the introduced cost model, four detailed cost functions are developed in MATLAB to be used as objective functions of optimization procedure by Differential Evolution algorithm. Two different case studies are selected from literature and two different groups of decision variables are considered for the optimization process. The optimization procedure aims to optimize the thermohydraulic and mechanical design of a BEM TEMA type shell and tube heat exchanger and minimize its manufacturing cost simultaneously. The results of the optimization procedure include the optimum design values of considered case studies which deliver the minimum cost of manufacturing. The obtained design values and costs are compared to the result of another research considering a similar case study. In the final step, a sensitivity analysis is carried out for all objective functions to find the effect of several manufacturing cost parameters on the resulted direct manufacturing cost.

The main goal of this research was finding the answer to the questions below:

1- How can the manufacturing cost of a shell and tube heat exchanger be estimated?
2- Which method of costing is more reasonable for estimation of the manufacturing processes?
3- What is the most suitable optimization method for designing a shell and tube heat exchanger?
4- How can the cost function be generated to estimate the manufacturing cost of shell and tube heat exchangers?

It is found that there are several costing methods for the cost estimation of shell and tube heat exchangers such as intuitive methods, parametric approaches, variant-based models, and generative cost estimation. The most suitable costing method to estimate the manufacturing cost of a shell and tube heat exchanger is an analytical generative model in which the effect of any change in design values or manufacturing processes will be projected in obtained cost estimation value. The optimization problem of a shell and tube heat exchanger is a nonlinear and multimodal problem including continuous and discrete variables. The Differential Evolution algorithm has proved its capability to handle complicated optimization problems and will deliver the global optimum solution in a fast and computationally efficient way. The cost function for estimation of the manufacturing cost of shell and tube heat exchanger must be generated based on a detailed cost model which comprehensively considers all the parameters affecting the design and cost values.

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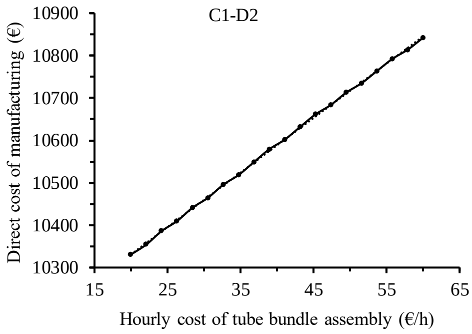
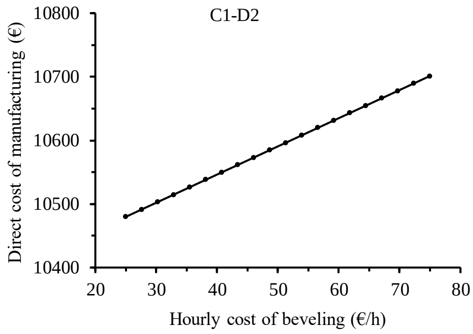
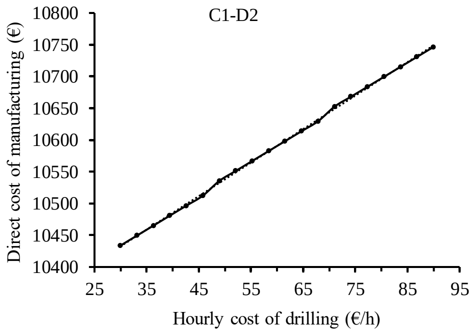
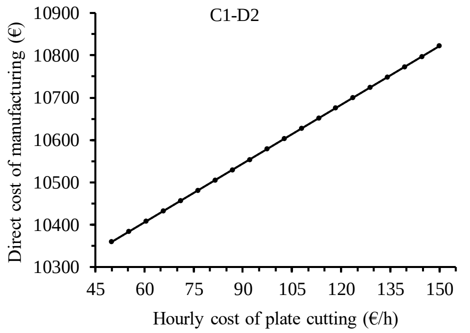
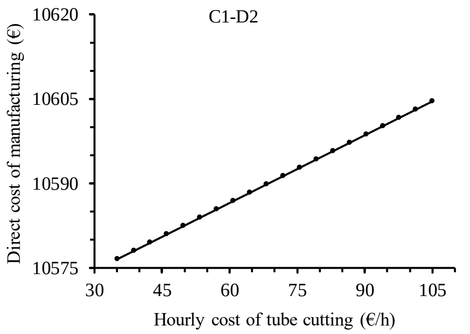
Scatter charts of the effect of manufacturing cost parameters on the direct cost of manufacturing for the case study 1 and the second group of decision variables.

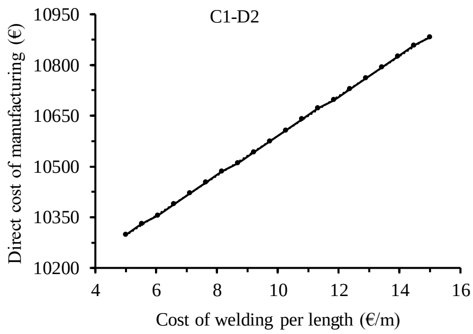


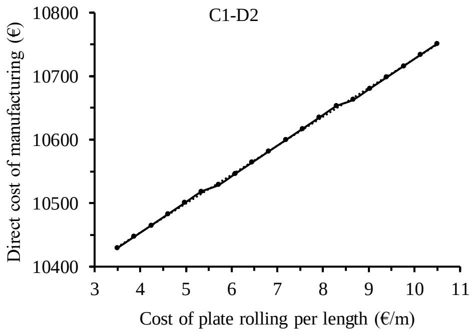


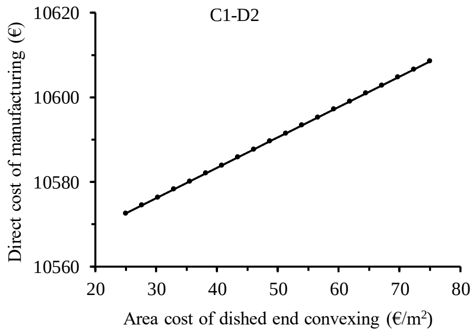




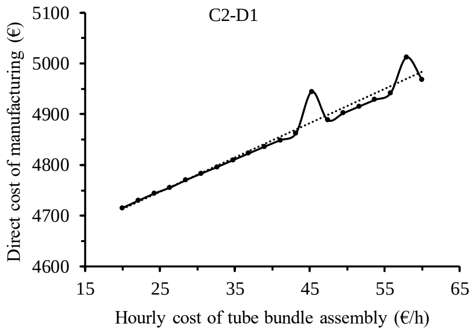


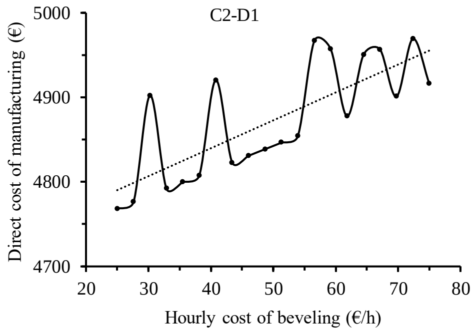


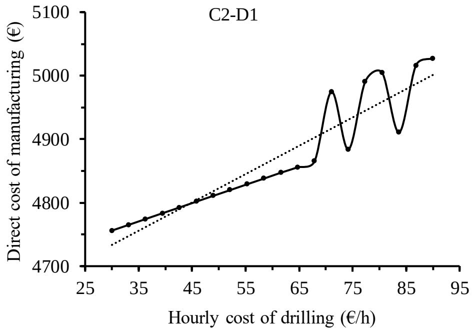


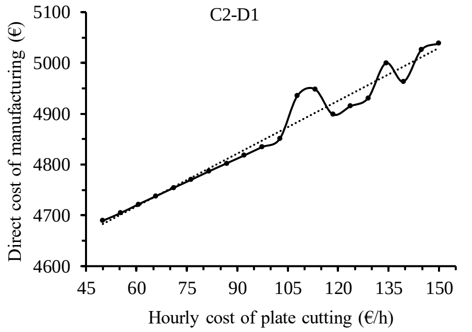


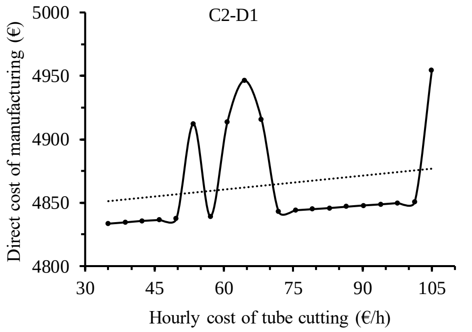
Scatter charts of the effect of manufacturing cost parameters on the direct cost of manufacturing for the case study 2 and the first group of decision variables.

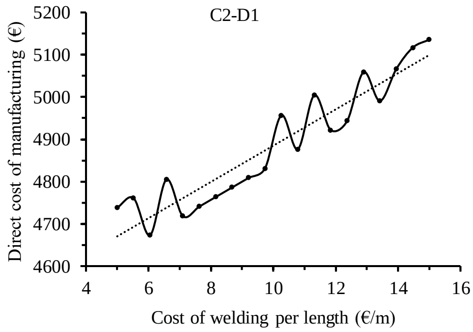


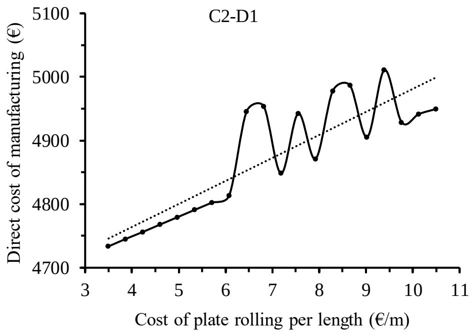


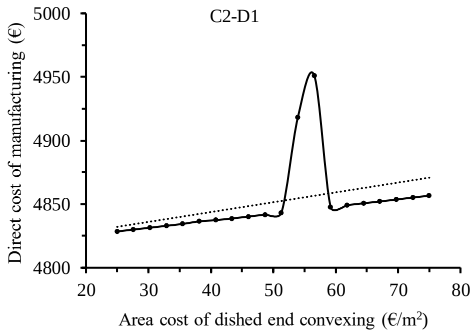




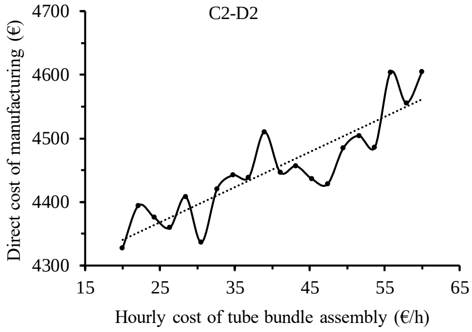


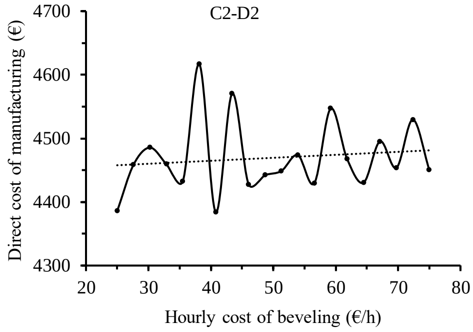


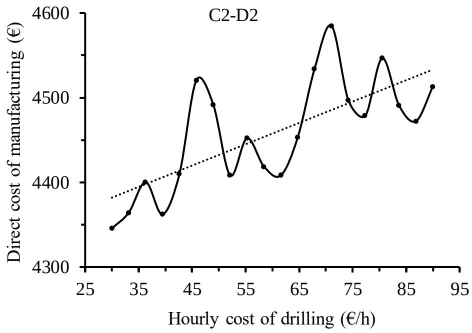


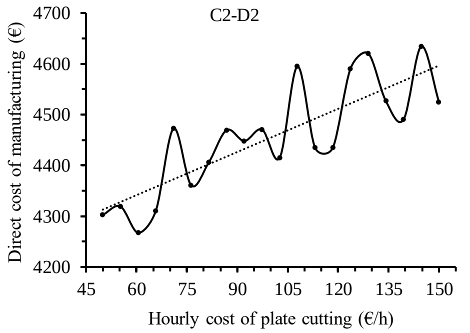


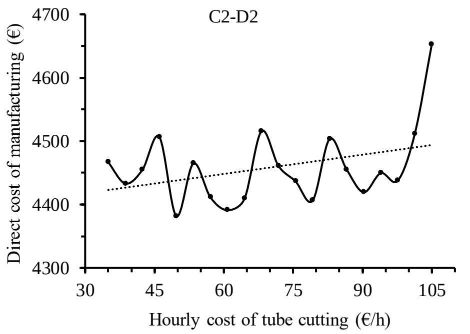
Scatter charts of the effect of manufacturing cost parameters on the direct cost of manufacturing for the case study 2 and the second group of decision variables.

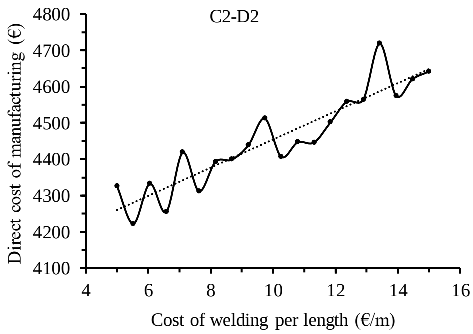


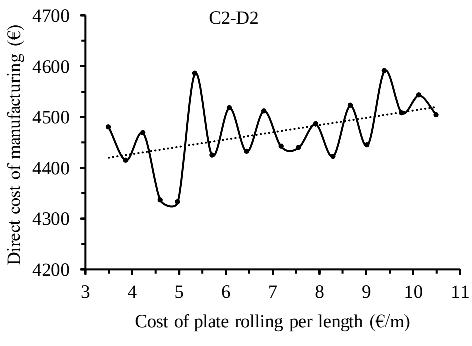


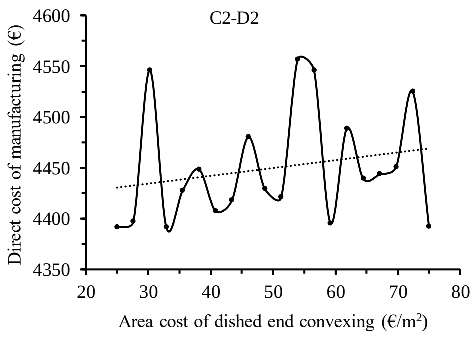












```
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
% Function:         S_MSE= objfun(FVr_temp, S_struct)
% Description:      Implements the cost function to be MINIMIZED
% Parameters:       FVr_temp(I_D)(I)    Parameter vector; contains the I_D decision variables
%                   S_Struct     (I)    A struct with a number of parameters: the following
are needed:
%                       S_Struct.I_D:                number of decision variables
%                       S_Struct.FVr_minbound(I_D): decision variable minimum boundaries
%                       S_Struct.FVr_maxbound(I_D): decision variable maximum boundaries
% Return value:      S_MSE.I_nc    (O)     Number of constraints. Constraints handled now by
penalties in objective function, so set to 0.
%                       S_MSE.FVr_ca  (O)     Constraint values. Constraints handled now by
penalties in objective function, so set to 0. (values >0 would mean distance to a constraint.)
%                   S_MSE.I_no    (O)    Number of objectives in case of doing multiobjective
optimization
%                   S_MSE.FVr_oa  (O)    Objective function values. Array when multiobjective
optimization.
%                    S_MSE.TheRest(O)    Whole bunch of other fields: related to particular
obj.function at hand.
%                                         Should be passed through to the front-end .m file
that runs the optimizer,
%                                        but for result interpretation only - doesn't affect
the optimization itself.
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
function S_MSE = objfunSTHX1W_Dscr_HBF(FVr_temp, S_struct, Cstruct)


FVr_minbound = S_struct.FVr_minbound;
FVr_maxbound = S_struct.FVr_maxbound;
I_D = S_struct.I_D;

constraints_ok=1;
constraints_violated = 0;
for i=1:I_D
    if ((FVr_temp(i)<FVr_minbound(i)) || (FVr_temp(i)>FVr_maxbound(i)))
        constraints_ok=0;                        % if constr. > 0 , not ok
        constraints_violated = constraints_violated+1;
    end
end
% 1. tube arrangement: 1: 30deg, 2: 60deg,3: sqaure/staggered, 4:inline
FVr_temp(1)=ceil(FVr_temp(1));
TubeArr = FVr_temp(1);
if ((FVr_temp(1)<1)|| (FVr_temp(1)>4))
    constraints_violated = constraints_violated+1;
    constraints_ok=0;
end

% 2. number of tube passes: 1, 2, 4, 6 or 8
FVr_temp(2) = floor(FVr_temp(2));
switch (FVr_temp(2))
    case 0
        Tp=1;
    case 1
        Tp=2;
    case 2
        Tp=4;
    case 3
        Tp=6;
    case 4
        Tp=8;
    otherwise
        Tp=-1;
        constraints_ok = 0;
        constraints_violated = constraints_violated+1;
end
FVr_temp(2)=Tp;

TEMA(1)='B';
TEMA(2)='E';
TEMA(3)='M';
       % 3. Hot flow in tubes: 1 if hot fluid in tube side, cold in shell side. Otherwise 0.
if (FVr_temp(3) < 1)
```

```
    FVr_temp(3) = 0;
else
    FVr_temp(3) = 1;
end

% 4 tube outer diametre [m]
FVr_temp(4) = ceil(FVr_temp(4));
TEMA_do =    [    9.52    12.70    15.88    19.05    22.22    25.40    31.75    38.1    50.8];
if ( (FVr_temp(4)>0) && (FVr_temp(4) <= 8) )
    do = TEMA_do(1,FVr_temp(4));
    s = 1.651;     % 12-2.769     14-2.108     16-1.651     18-1.245     20-0.889     22-0.711
24-0.559
    FVr_temp(4)=do*0.001;
else
    do=-1;
    s=-1;
    constraints_ok = 0;
    constraints_violated = constraints_violated+1;
end

% 5 tube length [m]
FVr_temp(5) = ceil(FVr_temp(5));
TEMA_L_tb = [ 1.219 1.829   2.438   3.048   3.658   4.877   6.096   7.315 ];
if ( (FVr_temp(5)>0) && (FVr_temp(5) <= 8) )
    L_tb = TEMA_L_tb(1,FVr_temp(5));
else
    L_tb = -1;
    constraints_ok = 0;
    constraints_violated = constraints_violated+1;
end

% 6 N_tubes, number of tubes per pass [-]: round up to make integer
FVr_temp(6) = ceil(FVr_temp(6));
N_tubes_pass = FVr_temp(6); % number of tubes PER PASS!!!

% 7 Number of sealing strip pairs
if ((FVr_temp(7) < 0) || (FVr_temp(7) > 7))
    FVr_temp(7) = -1;
    constraints_ok = 0;
    constraints_violated = constraints_violated+1;
else
    FVr_temp(7) = floor(FVr_temp(7));
end

% 8 Number of baffles
N_Baffles = floor(FVr_temp(8));
if (N_Baffles<2)
    N_Baffles=0; % to prevent division by zero if -1
    constraints_ok = 0;
    constraints_violated = constraints_violated+1;
end

% 9 baffle cut: processed after determining shell diameter

% 10 shell diameter [m]
TEMA_Dsh = [0.203 0.254 0.305 0.337 0.387 0.438 0.489 0.540 0.591 0.635 0.686 0.737 0.787
0.838 0.889 0.940 0.991 1.067 1.143 1.219 1.295 1.372 1.448 1.524];
FVr_temp(10) = ceil(FVr_temp(10));
if ( (FVr_temp(10)>0) && (FVr_temp(10) <= 24) )
    D_shO = TEMA_Dsh(1,FVr_temp(10));
else
    D_shO = -1;
    constraints_ok = 0;
    constraints_violated = constraints_violated+1;
end

% 9. continued...
s_sh = 0.01;
D_shI = D_shO-2*s_sh;
S_bf = (L_tb - (2*0.1*D_shO)) / (N_Baffles+1);
%[~, t_bf] = GetBaffleData(D_shI, S_bf);
Sbf_Dsh = S_bf/D_shI;
BC = 0.2 + (Sbf_Dsh-0.2)*(0.15/0.80) + FVr_temp(9);
```

```
% determine P_t / do (ratio of tube pitch to tube outside diameter [-]): 1.2 < Pt_do < 2.0
[D_OTL, D_ok] = GetDOTL(D_shI,TEMA(3),1);
constraints_ok=min(constraints_ok,D_ok);
if (constraints_ok==1)
    if (TubeArr < 2.001)
        K1 = [0.319 0.249 -1 0.175 -1 0.0743 -1 0.0365];
        n1 = [2.142 2.207 -1 2.285 -1 2.4990 -1 2.6750];
    else
        K1 = [0.215 0.156 -1 0.158 -1 0.0402 -1 0.0331];
        n1 = [2.207 2.291 -1 2.263 -1 2.6170 -1 2.6430];
    end
    %fprintf(1,'\nTube passes: %d',Tp);
    N_tubes=N_tubes_pass*Tp;
    P_do = 1.25*((1/N_tubes)*K1(Tp)*((D_OTL/(do*0.001))^n1(Tp)))^0.5;
else
    P_do=-1;
end

% 11. Material options: 1, 2 or 3
if ( (FVr_temp(11)>0) && (FVr_temp(11) <= 4) )
    FVr_temp(11) = ceil(FVr_temp(11));

    switch FVr_temp(11)
        case 1
            Material_opt= 1;
        case 2
            Material_opt= 2;
        case 3
            Material_opt= 3;
        case 4
            Material_opt= 4;
        otherwise
            Material_opt= -1;
    end
else
    FVr_temp(11)=-1
    constraints_ok = 0;
    constraints_violated = constraints_violated+1;
end

% 12. Shell sheet metal options: 1 to 9
if ( (FVr_temp(12)>0) && (FVr_temp(12) <= 9) )
    FVr_temp(12) = ceil(FVr_temp(12));

    switch FVr_temp(12)
        case 1
            sheet_opt= 1;
        case 2
            sheet_opt= 2;
        case 3
            sheet_opt= 3;
        case 4
            sheet_opt= 4;
        case 5
            sheet_opt= 5;
        case 6
            sheet_opt= 6;
        case 7
            sheet_opt= 7;
        case 8
            sheet_opt= 8;
        case 9
            sheet_opt= 9;
        otherwise
            sheet_opt= -1;
    end
else
    FVr_temp(12)=-1
    constraints_ok = 0;
    constraints_violated = constraints_violated+1;
end
```

```
% 13. baffle sheet metal options: 1 to 9
if ( (FVr_temp(13)>0) && (FVr_temp(13) <= 9) )
    FVr_temp(13) = ceil(FVr_temp(13));

    switch FVr_temp(13)
        case 1
            bflsheet_opt= 1;
        case 2
            bflsheet_opt= 2;
        case 3
            bflsheet_opt= 3;
        case 4
            bflsheet_opt= 4;
        case 5
            bflsheet_opt= 5;
        case 6
            bflsheet_opt= 6;
        case 7
            bflsheet_opt= 7;
        case 8
            bflsheet_opt= 8;
        case 9
            bflsheet_opt= 9;
        otherwise
            bflsheet_opt= -1;
    end
else
    FVr_temp(13)=-1;
    constraints_ok = 0;
    constraints_violated = constraints_violated+1;
end

N_constraints = 7;
g=zeros(N_constraints);
g(1) = (FVr_temp(4)+0.002) - (P_do*FVr_temp(4));
g(2) = P_do-2;
g(3) = 1.25-P_do;
g(4) = 0.2 - (L_tb/(N_Baffles+1))/D_shO;
g(5) = ((L_tb/(N_Baffles+1))/D_shO) - 1.2;  % actual limit is 1.0, not 1.2, but part of Ltb
is eaten by tubesheets &
% baffles so erring on safe side; model will weed out illegal ones
g(6) = BC-0.4;
g(7) = 0.15-BC;

for i=1:N_constraints
    if (g(i) < 0)
        g(i) = 0;
    else
        constraints_violated = constraints_violated+1;
        constraints_ok=0;
    end
end
FixedParams = GetFixedParams(Material_opt);
Waste_sheet_Area=0;
Waste_sheet_Bfl=0;
C_manufacturing=0;
C_material=0;
C_processing=0;

if (constraints_ok == 1)
    CandSol.TubeArr = FVr_temp(1);         % tube arrangement: 1: 60deg, 2: 60deg rot, 3:
sqaure/staggered, 4:inline
    CandSol.TubePasses = FVr_temp(2);   % number of tube passes: 1, 2, 4, 6 or 8
    CandSol.HotInTubes = FVr_temp(3);    % 1 if hot fluid in tube side, cold shell side.
Otherwise 0.
    CandSol.do = do*0.001;              % tube outside diameter [m]
    CandSol.P_do = P_do;                % ratio of tube pitch to tube outside diameter Pt/do
[-]
    CandSol.L_tb = L_tb;                % tube length [m]
    CandSol.SealingStrips = FVr_temp(7);% number of sealing strip pairs [-]
    CandSol.N_Baffles = N_Baffles;      % Number of baffles [-]
    CandSol.BaffleCut = BC;             % baffle cut [-]
    CandSol.D_shO = D_shO;              % shell diameter [m]
```

```
    Const.HeadType=1;                      % head type = 1 (rigid, fixed tubesheet)
    Const.delta_hole = 0.001;              % diameter of baffle hole = tube clearance + do [m]
    Const.baffle_clearance = 0.0025;       % space between baffle edge and shell [m]
    Const.t_Bfl = 0.005;                   % baffle plate thickness [m]
    Const.d_nozzle = 0.220;                % shell-side fluid inlet and outlet diametres [m]
    Const.d_tube_headentry = 0.220;        % tube-side fluid inlet and outlet diametres [m]
    Const.k_wall = FixedParams.metalprops.k;   % tube wall thermal conductivity [W/mK]
    Const.s_wall = s*0.001;                % tube wall thickness [m]

    Fluids = GetFluids();


    solution = ShellAndTubeB_HBF(CandSol,Const,Fluids,TEMA,0);

    if (solution.ok == 1)
        interest = FixedParams.EconData.interest;
        years = FixedParams.EconData.years;
        El_cost = FixedParams.EconData.El_cost;
        VAT = FixedParams.EconData.VAT;
        EtaPump = 0.70;
        EtaMotor = 0.85;
        hours = 7000;

        PumpingCost    =    hours*(10^-6)*El_cost    *    (solution.DpHot*solution.qVh    +
solution.DpCold*solution.qVc) / (EtaMotor*EtaPump);
    else
        PumpingCost = 10^9;
    end

    hxdata.Npasses = CandSol.TubePasses;
    hxdata.do_mm = CandSol.do*1000;
    hxdata.s_mm = Const.s_wall*1000;
    hxdata.P_mm = hxdata.do_mm * CandSol.P_do;
    hxdata.D_OTL = solution.D_OTL;
    hxdata.D_ShIn = solution.D_sh;
    hxdata.NtbPerPass = (solution.N_Tubes/solution.N_TubePasses);
    hxdata.N_HolesPerBaffle = solution.N_HolesPerBaffle;
    hxdata.N_bfls = solution.N_Baffles;
    hxdata.s_bfl = solution.t_bf;
    hxdata.LStraight = solution.L_tb_eff+(solution.N_Baffles*solution.t_bf);
% Lstraight = straight tube in pass INCLUDING covered by baffles, NOT INCLUDING inside
tubesheet
    hxdata.TotTbL_eff = solution.L_tb_eff*solution.N_TubePasses*hxdata.NtbPerPass;
% TOTAL sum of tube length available from effective heat transfer EXCLUDING part of tube
hidden under tubesheet or baffle/support plates
    hxdata.A_BflFr = solution.A_bfl;
% FRONTAL AREA OF BAFFLE PLATE!!! BEFORE DRILLING DA HOLES!!
    hxdata.SStripWidth = (0.5*solution.do) + (solution.D_sh-solution.D_OTL)*0.5;
    hxdata.StripPairs = CandSol.SealingStrips;

    if (solution.ok == 1)
        HmassRes = STHEmass_HBF(hxdata,FixedParams,'noplot.txt',TEMA,0);
        if (HmassRes.fock==1)
            solution.ok=0;
        end
    end

    if (solution.ok == 1)

% this part finds the waste area of standard sheet metal sizes for making shell in case shell
diameter is bigger than available commercial tubes

        Sh_middle_D = solution.D_sh + HmassRes.s_shell;
        Sh_sheet_Cut_L = Sh_middle_D * pi;
        Sh_sheet_Cut_W = HmassRes.L_shell;
        if Sh_middle_D <= 0.6
            sheet_opt = 0;
% sheet metal is not used when commercial seamless tubes are available according to shell
diameter
            StdShTbL = 12;                        % a sample standard seamless tube length
(m)
        else
            switch sheet_opt              % Length and width of comercial plate, unit: m
```

```
            case 1
                Sh_sheet_L=3;
                Sh_sheet_W=12;
            case 2
                Sh_sheet_L=4;
                Sh_sheet_W=16;
            case 3
                Sh_sheet_L=5;
                Sh_sheet_W=15;
            case 4
                Sh_sheet_L=6;
                Sh_sheet_W=12;
            case 5
                Sh_sheet_L=6;
                Sh_sheet_W=16;
            case 6
                Sh_sheet_L=4;
                Sh_sheet_W=12;
            case 7
                Sh_sheet_L=5;
                Sh_sheet_W=12;
            case 8
                Sh_sheet_L=6;
                Sh_sheet_W=20;
            case 9
                Sh_sheet_L=7;
                Sh_sheet_W=15;
        end

        if ((Sh_sheet_Cut_L <= Sh_sheet_L) && (Sh_sheet_Cut_W<=Sh_sheet_W))
            sh_plate_situation = 1;
            Ratio1= floor(Sh_sheet_L / Sh_sheet_Cut_L);
            Ratio2= floor(Sh_sheet_W / Sh_sheet_Cut_L);
            Ratio3= floor(Sh_sheet_W / Sh_sheet_Cut_W);
            Ratio4= floor(Sh_sheet_L / Sh_sheet_Cut_W);
            A_Ratio1= Ratio1*Ratio3;
            A_Ratio2= Ratio2*Ratio4;
            A_Ratio3=     floor((Sh_sheet_L*Sh_sheet_W)     /     (Sh_sheet_Cut_L     *
Sh_sheet_Cut_W));
            Ratio=[A_Ratio1,A_Ratio2,A_Ratio3];
            Max_Ratio= max(Ratio);
            Waste_sheet_Area = (Sh_sheet_L*Sh_sheet_W) - (Max_Ratio * Sh_sheet_Cut_L *
Sh_sheet_Cut_W);

        elseif ((Sh_sheet_Cut_L > Sh_sheet_L) || (Sh_sheet_Cut_W>Sh_sheet_W))
            sh_plate_situation = 2;
            Ratio1= ceil(Sh_sheet_Cut_L / Sh_sheet_L);
            Ratio2= ceil(Sh_sheet_Cut_L / Sh_sheet_W);
            Ratio3= ceil(Sh_sheet_Cut_W / Sh_sheet_W);
            Ratio4= ceil(Sh_sheet_Cut_W / Sh_sheet_L);
            A_Ratio1= Ratio1*Ratio3;
            A_Ratio2= Ratio2*Ratio4;
            A_Ratio3= ceil((Sh_sheet_Cut_L * Sh_sheet_Cut_W) / (Sh_sheet_L*Sh_sheet_W));
            Ratio=[A_Ratio1,A_Ratio2,A_Ratio3];
            Min_Ratio= min(Ratio);
            Waste_sheet_Area = (Min_Ratio * Sh_sheet_L*Sh_sheet_W) - (Sh_sheet_Cut_L *
Sh_sheet_Cut_W);

        end

    end

    % this part calculates the waste area of baffles using the same
    % standard plates sizes used to manufacture the shell
    % finding max number of circles fet into a rectangular plate
    % Misha Lavrov (https://math.stackexchange.com/users/383078/misha-lavrov), Maximum
number    of    circle    packing    into    a    rectangle,    URL    (version:    2017-12-03):
https://math.stackexchange.com/q/2548599
    switch bflsheet_opt                   % Length and width of comercial plate, unit: m
        case 1
            bfl_sheet_L=3;
            bfl_sheet_W=12;
        case 2
```

```
                bfl_sheet_L=4;
                bfl_sheet_W=16;
            case 3
                bfl_sheet_L=5;
                bfl_sheet_W=15;
            case 4
                bfl_sheet_L=6;
                bfl_sheet_W=12;
            case 5
                bfl_sheet_L=6;
                bfl_sheet_W=16;
            case 6
                bfl_sheet_L=4;
                bfl_sheet_W=12;
            case 7
                bfl_sheet_L=5;
                bfl_sheet_W=12;
            case 8
                bfl_sheet_L=6;
                bfl_sheet_W=20;
            case 9
                bfl_sheet_L=7;
                bfl_sheet_W=15;
        end

        m_c1 =floor(((bfl_sheet_L/(solution.D_bf/2))-1)/2);
        n_r1 = floor((((bfl_sheet_W/(solution.D_bf/2))-2)/sqrt(3))+1);
        m_c2 =floor(((bfl_sheet_W/(solution.D_bf/2))-1)/2);
        n_r2 = floor((((bfl_sheet_L/(solution.D_bf/2))-2)/sqrt(3))+1);
        Bfl_circle_No=[m_c1*n_r1,m_c2*n_r2];
        Max_Bfl_circle_No = max(Bfl_circle_No);
        Waste_sheet_Bfl    =    (bfl_sheet_L    *    bfl_sheet_W)    -    Max_Bfl_circle_No
*(0.25*pi*(solution.D_bf^2) - solution.A_bfl);

        % Manufacturing operation cost parameters

        cH_assembly = Cstruct.cH_assembly;             % tube bundle assembly, labor only €
        cH_bevel = Cstruct.cH_bevel; % baffle plate drilling,€/h(same as shell plate beveling)
        cH_drill = Cstruct.cH_drill;                   % baffle plate drilling, €/h
        cH_c = Cstruct.cH_c;                      % plate cutting, €/h
        cH_c_Tb=Cstruct.cH_c_Tb;                      % Tube cutting, €/m
        cH_c_ShTb= Cstruct.cH_c_ShTb;                   % Shell tube cutting (Dsh<0.6 m)
        cL_weld = Cstruct.cL_weld;                    % welding cost per length €/m
        cL_roll = Cstruct.cL_roll;                     % rolling cost per length €/m
        cA_dished = Cstruct.cA_dished;                  % dished head shaping per area €/m^2

        v_drill = 0.3;                  % drilling speed, m/min
        v_cut = 1.0;                    % cutting speed, m/min
        v_bev = 3.0;                    % cutting speed, m/min
        ST_tb = 5.0;                    % 1 tube through 1 hole, seconds
        L_l = 5.0/1000;                 % drill head lead travel, mm->m
        L_ot = 5.0/1000;                % drill head overtravel, mm->m
        L_pt = 5.0/1000;                % drill head pre-travel, mm->m


        % SHELL MANUFACTURING COST

        % Shell made from seamless tubes (3 cases happen):
        if (sheet_opt == 0)
            if (HmassRes.L_shell< StdShTbL)
                L_shtb_cut =  pi * Sh_middle_D;                     % cutting length
                L_shtb_chmf = 2 * L_shtb_cut;                       % chamfering length
                L_TbSheet_weld = 2 * L_shtb_cut;                           % welding length
tubesheet to shell
                C_sh_c = (L_shtb_cut / v_cut / 60)* cH_c_ShTb;
                C_sh_chmf = (L_shtb_chmf / v_bev / 60)* cH_bevel;
                C_TbSheet_weld = L_TbSheet_weld * cL_weld;
                C_sh_oper = C_sh_c+ C_sh_chmf+ C_TbSheet_weld;

            elseif (HmassRes.L_shell== StdShTbL)
                L_shtb_cut =  pi * Sh_middle_D;
                L_shtb_chmf = 2 * L_shtb_cut;
                L_TbSheet_weld = 2 * L_shtb_cut;
```

```
            C_sh_chmf = (L_shtb_chmf / v_bev / 60)* cH_bevel;
            C_TbSheet_weld = L_TbSheet_weld * cL_weld;
            C_sh_oper = C_sh_chmf+ C_TbSheet_weld;

        elseif (HmassRes.L_shell> StdShTbL)
            N_sh_Tb = ceil(HmassRes.L_shell/StdShTbL);
            L_shtb_cut =  pi * Sh_middle_D;
            L_shtb_chmf = 2 * L_shtb_cut * N_sh_Tb;
            L_shTb_weld = L_shtb_cut * (N_sh_Tb-1);
            L_TbSheet_weld = 2 * L_shtb_cut;
            C_sh_c = (L_shtb_cut / v_cut / 60)* cH_c_ShTb;
            C_sh_chmf = (L_shtb_chmf / v_bev / 60)* cH_bevel;
            C_shTb_weld = L_shTb_weld *cL_weld;
            C_TbSheet_weld = L_TbSheet_weld * cL_weld;
            C_sh_oper = C_sh_c+ C_sh_chmf+C_shTb_weld+ C_TbSheet_weld;
        end

        % shell made from rectangular plates:
    elseif (sh_plate_situation ==1)
        L_shSheet_cut =  Sh_sheet_Cut_L+Sh_sheet_Cut_W;                    % cutting
length
        L_shSheet_chmf = L_shSheet_cut;                                 % chamfering
length
        shSheet_roll_L= Sh_sheet_Cut_L;                                % Shell plate
rolling
        L_shSeam_weld = Sh_sheet_Cut_W;                                 % shell seam
welding
        L_TbSheet_weld = 2 * Sh_sheet_Cut_L;                            % tube sheet
welding length
        C_sh_c = (L_shSheet_cut / v_cut / 60)* cH_c;
        C_sh_chmf = (L_shSheet_chmf / v_bev / 60)* cH_bevel;
        C_sh_roll = shSheet_roll_L * cL_roll;
        C_shSeam_TbSheet_weld = (L_shSeam_weld+L_TbSheet_weld) * cL_weld;
        C_sh_oper = C_sh_c + C_sh_chmf + C_sh_roll+ C_shSeam_TbSheet_weld;

    elseif (sh_plate_situation ==2)
        N_sh_sheet = Min_Ratio;
        L_shSheet_cut =  Sh_sheet_Cut_L+ Sh_sheet_Cut_W;                   % cutting
length
        L_shSheet_chmf = L_shSheet_cut;                                 % chamfering
length

        if (Sh_sheet_Cut_L > Sh_sheet_L)                                % shell seam
welding
            L_shSeam_weld = Sh_sheet_Cut_W * N_sh_sheet;
            shSheet_roll_L= Sh_sheet_Cut_L;                            % Shell plate
rolling
        elseif (Sh_sheet_Cut_W> Sh_sheet_W)
            L_shSeam_weld = Sh_sheet_Cut_W + (N_sh_sheet-1)*Sh_sheet_Cut_L;
            shSheet_roll_L= Sh_sheet_Cut_L*N_sh_sheet;
        end

        L_TbSheet_weld = 2 * Sh_sheet_Cut_L;                                % flange
welding length
        C_sh_c = (L_shSheet_cut / v_cut / 60)* cH_c;
        C_sh_chmf = (L_shSheet_chmf / v_bev / 60)* cH_bevel;
        C_sh_roll = shSheet_roll_L * cL_roll;
        C_shSeam_TbSheet_weld = (L_shSeam_weld+L_TbSheet_weld) * cL_weld;
        C_sh_oper = C_sh_c + C_sh_chmf + C_sh_roll+ C_shSeam_TbSheet_weld;

    end

    % TUBESHEET MANUFACTURING COST

    L_TbSheet_cut = HmassRes.D_Flng;
    L_TbSheet_bev = L_TbSheet_cut;
    L_TbSheet_drill = HmassRes.L_drill_Ts;
    C_TbSheet_cut = (L_TbSheet_cut /v_cut/60) * cH_c;
    C_TbSheet_bev = (L_TbSheet_bev / v_bev/ 60) * cH_bevel;
    C_TbSheet_drill = (L_TbSheet_drill/ v_drill/60) * cH_drill;
    C_TbSheet_oper = C_TbSheet_cut + C_TbSheet_bev + C_TbSheet_drill;
```

```
% BAFFLE MANUFACTURING COST

%          L_Bfls_cut = solution.Lcut_Bfl*solution.N_Baffles;
%          L_Bfls_bev = L_Bfls_cut;
%          L_Bfls_drill = HmassRes.L_drill_Bfl;
%          C_Bfls_cut = (L_Bfls_cut /v_cut/60) * cH_c;

%          C_Bfls_bev = (L_Bfls_bev / v_bev/ 60) * cH_bevel;
%          C_Bfls_drill = (L_Bfls_drill/ v_drill/60) * cH_drill;
%          C_Bfls_oper = C_Bfls_cut + C_Bfls_bev + C_Bfls_drill;

% cutting baffle basic shape
Lcut_Bfls = solution.Lcut_Bfl*solution.N_Baffles;
Lcut_Bfls = Lcut_Bfls + (2*CandSol.SealingStrips)*((2*hxdata.LStraight)+2*hxdata.SStripWidth); % cutting sealing strips
Lcut_Bfls = Lcut_Bfls + (solution.N_Baffles*(2*CandSol.SealingStrips)*((2*hxdata.SStripWidth) + solution.t_bf)); % cutting notches for sealing strips into baffles

T_BfCut = (15/60)*solution.N_Baffles + (2/60)*solution.N_Baffles + ((Lcut_Bfls/v_cut)/60); %setup time: 30minr per plate
C_BfCut = cH_c * T_BfCut;

%beveling length = cutting length
T_BfBevel = (15/60)*solution.N_Baffles + (2/60)*solution.N_Baffles +((Lcut_Bfls/v_bev)/60); %setup time: quarter an hour per plate to move & load up, 5min to set up
C_BfBevel = cH_bevel * T_BfBevel;

L_Bfl_drill = HmassRes.L_drill_Bfl + (solution.N_TubePasses*hxdata.NtbPerPass)*(L_l+L_ot+L_pt);
T_BfDrill = (solution.N_HolesPerBaffle*2/3600) + (2/60)*solution.N_Baffles + (5/60)*solution.N_Baffles + ((L_Bfl_drill/v_drill)/60); % setup time: 2 min / baffle plate; loadup: 5min/plate
C_BfDrill = cH_drill * T_BfDrill;

C_Bfls_oper=C_BfCut+C_BfBevel+C_BfDrill;


% CHANNEL MANUFACTURING COST
% channel inside diameter = shell inside diameter
% similar process to shell manufacturing

% channel made from seamless tubes (3 cases happen):
Ch_middle_D=HmassRes.D_ChIn+ HmassRes.s_channelshell;
L_channell= HmassRes.L_fhead+HmassRes.L_rhead;
if (sheet_opt == 0)
    if (L_channell < StdShTbL)
        L_chtb_cut =2 *  pi * Ch_middle_D;               % cutting length
        L_chtb_chmf = 2* L_chtb_cut;                     % chamfering length
        L_flng_weld = 2* L_chtb_cut;                     % welding length flange to channel
        C_ch_c = (L_chtb_cut / v_cut / 60)* cH_c_ShTb;
        C_ch_chmf = (L_chtb_chmf / v_bev / 60)* cH_bevel;
        C_flng_weld = L_flng_weld * cL_weld;
        C_ch_oper = C_ch_c+ C_ch_chmf+ C_flng_weld;

    elseif (L_channell== StdShTbL)
        L_chtb_cut = 2* pi * Ch_middle_D;
        L_chtb_chmf = 2 * L_chtb_cut;
        L_flng_weld = 2 * L_chtb_cut;
        C_ch_chmf = (L_chtb_chmf / v_bev / 60)* cH_bevel;
        C_flng_weld = L_flng_weld * cL_weld;
        C_ch_oper = C_ch_chmf+ C_flng_weld;

    elseif (L_channell> StdShTbL)
        N_ch_Tb = ceil(L_channell/StdShTbL);
        L_chtb_cut = 2* pi * Ch_middle_D;
        L_chtb_chmf = 2 * L_chtb_cut * N_ch_Tb;
        L_chTb_weld = L_chtb_cut * (N_ch_Tb-1);
        L_flng_weld = 2 * L_chtb_cut;
        C_ch_c = (L_chtb_cut / v_cut / 60)* cH_c_ShTb;
```

```
                C_ch_chmf = (L_chtb_chmf / v_bev / 60)* cH_bevel;
                C_chTb_weld = L_chTb_weld *cL_weld;
                C_flng_weld = L_flng_weld * cL_weld;
                C_ch_oper = C_ch_c+ C_ch_chmf+C_chTb_weld+ C_flng_weld;
            end

            % channel made from rectangular plates:
        else
            L_chtb_cut = 2* pi * Ch_middle_D + L_channell;                  % cutting length
            L_chtb_chmf = 4* pi * Ch_middle_D + L_channell;              % chamfering length
            L_flng_seam_weld =L_chtb_chmf;                      % welding length flange to channel
            L_ch_roll = pi * Ch_middle_D;
            C_ch_c = (L_chtb_cut / v_cut / 60)* cH_c_ShTb;
            C_ch_chmf = (L_chtb_chmf / v_bev / 60)* cH_bevel;
            C_flng_weld = L_flng_seam_weld * cL_weld;
            C_ch_roll = L_ch_roll*cL_roll;
            C_ch_oper = C_ch_c+ C_ch_chmf+ C_flng_weld+C_ch_roll;
        end

        % torispherical dished end plate of channels

        A_dished =2 *  1.69 * (pi * HmassRes.D_ChIn^2)/4;
        L_ch_dished_weld = 2 * pi * Ch_middle_D;
        C_ch_end_dishing = A_dished * cA_dished;
        C_ch_end_weld = L_ch_dished_weld * cL_weld;
        C_ch_end_oper = C_ch_end_dishing + C_ch_end_weld;

        C_ch_oper = C_ch_oper+C_ch_end_oper;


        % TUBE BUNDLE ASSEMBLY

        StdTbL=12;                                                         % Tube side standard
commercial tube length (m)
        L_Tb_raw = HmassRes.L_shell+ 2*HmassRes.s_tbplate;           % including tube sheet
tickness
        L_Tb_raw_cut = solution.do*pi*solution.N_Tubes;
        L_Tb_raw_chmf = L_Tb_raw_cut;
        L_Tb_raw_weld = L_Tb_raw_cut;
        L_Tb_to_TbSheet_roll=L_Tb_raw_cut*2;
        L_Tb_to_TbSheet_weld=L_Tb_to_TbSheet_roll;
        C_Tb_raw_cut = (L_Tb_raw_cut/v_cut/60)* cH_c_Tb;
        C_Tb_to_TbSheet_roll=L_Tb_to_TbSheet_roll*cL_roll;
        C_Tb_to_TbSheet_weld=L_Tb_to_TbSheet_weld*cL_weld;
        if (L_Tb_raw > StdTbL)
            N_Tb_welded=ceil(L_Tb_raw/StdTbL);
            C_Tb_raw_chmf = (L_Tb_raw_chmf/v_bev/ 60) * cH_bevel*(N_Tb_welded-1);
            C_Tb_raw_weld = L_Tb_raw_weld*cL_weld*(N_Tb_welded-1);
        else
            C_Tb_raw_chmf = 0;
            C_Tb_raw_weld  =0;
        end
        T_assembly = 0.5 + ((solution.N_HolesPerBaffle*solution.N_Baffles)*ST_tb/3600);
        T_assembly = T_assembly + (2*CandSol.SealingStrips)*(2/60)*solution.N_Baffles;
% assume 2 minutes to attach 1 sealing strip to 1 baffle.
        T_assembly = T_assembly + ((20/60)*solution.N_Baffles);
        switch TEMA(3)
            case 'L'
                T_assembly = T_assembly * 1.1;
            case 'M'
                T_assembly = T_assembly * 1.15;
            case 'T'
                T_assembly = T_assembly * 1.25;
            case 'U'
                T_assembly = T_assembly * 1.05;
        end
        C_assembly = cH_assembly*T_assembly;

C_Tb_bundle_oper=C_Tb_raw_cut+C_Tb_to_TbSheet_roll+C_Tb_to_TbSheet_weld+C_Tb_raw_chmf+C_Tb_
raw_weld+C_assembly;


        % DETERMINE TOTAL CAPITAL INVESTMENT
```

```
        % Material cost
        cM_sh = FixedParams.metalprops.price;                        % [€/kg];
        cM_bf = FixedParams.metalprops.price;                        % [€/kg];
        cM_ts = FixedParams.metalprops.price * 2;                      % [€/kg]; multiplied by 2
due to forged material
        cM_o = 2.0;                                                  % [€/kg];
        cM_tb = 2.40 + (180*(do^-2)); % estimate tube metal cost based on tube diameter
        if (hxdata.LStraight > 20.0)
            cM_tb = cM_tb*1.2;
        end

        C_sh = cM_sh*HmassRes.m_sh;      % shell cost [€]
        C_tb = cM_tb*HmassRes.m_tb;      % heat transfer area cost [€]
        C_bfl = cM_bf*HmassRes.m_bfl;    % baffle/support plate cost [€]
        C_ts = cM_ts*HmassRes.m_ts;      % tube sheet cost [€]
        C_ch = cM_sh*HmassRes.m_ch;     % channel cost (assume metal spec.cost same as shell)
[€]
        C_flng = cM_sh*HmassRes.m_flng;  % flange cost (assume metal spec.cost same as tube
sheet) [€]
        C_o = cM_o*HmassRes.m_other;     % cost of remaining compontents
        C_waste_shSheet  =  Waste_sheet_Area  *HmassRes.s_shell*  FixedParams.metalprops.rho
*cM_sh;
        C_Waste_sheet_Bfl = Waste_sheet_Bfl * solution.t_bf * FixedParams.metalprops.rho *
cM_bf;
        C_material       =       C_sh+C_tb+C_bfl+C_ts+C_ch+C_flng+C_o+       C_waste_shSheet+
C_Waste_sheet_Bfl; % material cost


        % Other cost components
        C_processing   =   C_sh_oper   +   C_TbSheet_oper   +   C_Bfls_oper   +C_Tb_bundle_oper+
C_ch_oper+(3*cM_o*HmassRes.m_other);  % processing cost 25 percent of total manufacturing
        C_manufacturing = C_material+C_processing;
        Fr_overhead = 0.30;              % Caputo et al 2013: "overhead 20%, markup 30%"
        Fr_profit = 0.10;
        Fr_contingency = 0.05;
        Fr_Transportation = 0.05;
        Fr_TotalMarkup = Fr_overhead + Fr_profit + Fr_contingency + Fr_Transportation;

        C_FOB = (1+VAT)*C_manufacturing / (1-Fr_TotalMarkup);

        C_module = 1.0 * C_FOB * 3.3;
        ann = ((1+interest)^years)*interest / ( ((1+interest)^years) -1);
        amort = ann * C_module;
        if (solution.Tho_actual<Fluids.Tho)
            pen = 0;

        else
            pen = (10^6)  +  ((10^6)*(solution.Tho_actual - Fluids.Tho));
        end
    else
        amort = 10^9;
        PumpingCost = 10^9;
        pen = 10^9;
        C_FOB = -1;

        HmassRes.L_tot = 0 ;
        HmassRes.D_tot = 0 ;
        HmassRes.s_shell = 0 ;
        HmassRes.s_tbplate= 0 ;
        HmassRes.s_fChannelcover = 0 ;
        HmassRes.s_rChannelcover = 0 ;
        HmassRes.s_channelshell = 0 ;        %       fprintf(1,'FAIL (calc)\n');
    end

    F_cost = amort + PumpingCost +pen;

    solution.ManufacturingCost=C_manufacturing;
    solution.MaterialCost=C_material;
    solution.ProcessCost=C_processing;
    solution.AreaCost = amort;
    solution.PumpingCost = PumpingCost;
    solution.F_cost = F_cost;
```

```
    S_MSE.TubeArr = solution.TubeArr ;
    S_MSE.N_TubePasses = solution.N_TubePasses ;
    S_MSE.N_Tubes = solution.N_Tubes ;
    S_MSE.N_Baffles = solution.N_Baffles ;
    S_MSE.BC = BC;
    S_MSE.S_bf = solution.S_bf ;
    S_MSE.S_end = solution.S_end ;
    S_MSE.Sbf_Ds = solution.Sbf_Ds;
    S_MSE.HotInTubes = solution.HotInTubes ;
    S_MSE.A_tot = solution.A_tot ;
    S_MSE.A_eff = solution.A_eff ;
    S_MSE.t_sh = HmassRes.s_shell ;
    S_MSE.t_bf = solution.t_bf;
    S_MSE.t_ts = HmassRes.s_tbplate;
    S_MSE.t_fchc = HmassRes.s_fChannelcover;
    S_MSE.t_rchc = HmassRes.s_rChannelcover;
    S_MSE.t_chs = HmassRes.s_channelshell;
    S_MSE.do = solution.do ;
    S_MSE.P_do = solution.P_do ;
    S_MSE.L_tb = solution.L_tb ;
    S_MSE.L_tb_eff = solution.L_tb_eff ;
    S_MSE.L_tot = HmassRes.L_tot ;
    S_MSE.D_tot = HmassRes.D_tot ;
    S_MSE.D_sh = solution.D_sh ;
    S_MSE.D_shO = solution.D_shO ;
    S_MSE.D_OTL = solution.D_OTL ;
    S_MSE.U = solution.U ;
    S_MSE.Dp_tb = solution.Dp_tb ;
    S_MSE.Dp_sh = solution.Dp_sh ;
    S_MSE.h_sh = solution.h_sh ;
    S_MSE.h_tb = solution.h_tb ;
    S_MSE.w_sh = solution.w_sh ;
    S_MSE.w_tb = solution.w_tb ;
    S_MSE.C_FOB = C_FOB;
    S_MSE.C_manufacturing=solution.ManufacturingCost;
    S_MSE.C_material=solution.MaterialCost;
    S_MSE.C_processing=solution.ProcessCost;
    S_MSE.AreaCost = solution.AreaCost ;
    S_MSE.PumpingCost = solution.PumpingCost ;
    S_MSE.F_cost = F_cost ;
    S_MSE.pen = pen ;
    S_MSE.Tho = Fluids.Tho ;
    S_MSE.Tho_actual = solution.Tho_actual ;
    S_MSE.Material_opt=Material_opt;
    S_MSE.Sh_sheet_opt=sheet_opt;
    S_MSE.bfl_sheet_opt=bflsheet_opt;
    S_MSE.waste_shSheet=Waste_sheet_Area;
    S_MSE.Waste_sheet_Bfl= Waste_sheet_Bfl;
else

    S_MSE.TubeArr = -1;
    S_MSE.N_TubePasses = -1;
    S_MSE.N_Tubes = 0;
    S_MSE.N_Baffles = -1;
    S_MSE.BC = -1;
    S_MSE.S_bf = -1;
    S_MSE.S_end = -1 ;
    S_MSE.Sbf_Ds = -1;
    S_MSE.HotInTubes = -1;
    S_MSE.A_tot = -1;
    S_MSE.A_eff = -1;
    S_MSE.t_sh = -1;
    S_MSE.t_bf = -1;
    S_MSE.t_ts = -1;
    S_MSE.t_fchc = -1;
    S_MSE.t_rchc = -1;
    S_MSE.t_chs = -1;
    S_MSE.do = -1;
    S_MSE.P_do = -1;
    S_MSE.L_tb = -1;
    S_MSE.L_tb_eff = -1;
    S_MSE.L_tot = -1;
    S_MSE.D_tot = -1;
```

```
    S_MSE.D_sh = -1;
    S_MSE.D_shO = -1;
    S_MSE.D_OTL = -1;
    S_MSE.U = -1;
    S_MSE.Dp_tb = -1;
    S_MSE.Dp_sh = -1;
    S_MSE.h_sh = -1;
    S_MSE.h_tb =-1;
    S_MSE.w_sh = -1;
    S_MSE.w_tb = -1;
    S_MSE.C_FOB = -1;
    S_MSE.C_manufacturing=-1;
    S_MSE.C_material=-1;
    S_MSE.C_processing=-1;
    S_MSE.AreaCost = -1;
    S_MSE.PumpingCost = -1;
    F_cost = (10^10)*(constraints_violated+1);
    S_MSE.F_cost = F_cost;
    S_MSE.pen = -1 ;
    S_MSE.Tho = -1 ;
    S_MSE.Tho_actual = -1 ;
    S_MSE.Material_opt= -1;
    S_MSE.Sh_sheet_opt=-1;
    S_MSE.bfl_sheet_opt=-1;
    S_MSE.waste_shSheet=-1;
    S_MSE.Waste_sheet_Bfl=-1;
end
if (S_MSE.F_cost < -1)
    fprintf(1,'\n Foooooock.... \n');
    F_cost = (10^10)*(N_constraints+1);
    S_MSE.F_cost = (10^10)*(N_constraints+1);
end
if (isreal(S_MSE.F_cost)~=1)
    F_cost = (10^10)*(N_constraints+2);
    S_MSE.F_cost = (10^10)*(N_constraints+2);
end
%----strategy to put everything into a cost function------------
S_MSE.I_nc = 0;             % no constraints as far as deopt.m is concerned
S_MSE.FVr_ca = 0;           % no constraint array as far as deopt.m is concerned
S_MSE.I_no = 1;             % number of objectives (costs)
S_MSE.FVr_oa = F_cost;
end

function FixedParams = GetFixedParams(Material_opt)
%tbsizes=[10 12 14 16 18 20 22 25 28 30 35 ];
ofuntp = 'I';                       % objective function type,'A': minimize area
% 'm': minimize mass
% 'I': minimize investment cost
% 'C': minimize operating + investment costDT=5;   % terminal temperature difference
wmaxh_max = 2.0;                    % max highest velocity of steam between tubes
wnzl_sqrtrho = (1500^.5);         % max velocity at nozzle: (1500/rho)^0.5; limit: w*(rho^.5)
< (1500^.5)
%dpcmax = 0.5;                      % [bar]
L_max = 15;
D_max = 3.5;
FixedParams.ofuntp = ofuntp;
FixedParams.wmaxh_max = wmaxh_max;
FixedParams.wnzl_sqrtrho = wnzl_sqrtrho;
FixedParams.L_max = L_max;
FixedParams.D_max = D_max;

sizingdata.ptbmin=-0.1;             % tube-side min p [MPa]
sizingdata.ptbmax=0.5;              % tube-side max p [MPa]
sizingdata.pshmin=-0.1;             % shell-side min p [MPa]
sizingdata.pshmax=0.5;               % shell-side max p [MPa] %Ttbmax=fscanf(fid,'%g', [1]);
% tube-side max T [°C] % Tshmax=fscanf(fid,'%g', [1]);               % shell-side max T [°C]
FixedParams.sizingdata = sizingdata;

switch Material_opt
    case 1                                  % Carbon steel P235GH (1.0345)
        metalprops.Et = 210*1000;           % N/mm2: Young's modulus, GPa=N/mm2
        metalprops.nyy = 0.3;              % [-]:   Poisson's number
```

```
        metalprops.nk = 3.0;                  % [-] nk=3; SFS 2862, 5.1 Kimmoinen lommahdus
(pp.184) (nk for calculating elastic deformation)
        metalprops.sigmal = 215;          % Laskentalujuus, GPa=N/mm2 (calculation  strength)
        metalprops.n = 2;                    % [-] varmuuskerroin (safety factor)
        metalprops.k = 51;                % tube wall thermal conductivity [W/mK]
        metalprops.rho= 7850;                  % material density[kg/m3]
        metalprops.price= 0.55;                  %[€/kg]
        FixedParams.metalprops = metalprops;

    case 2                                   %     X5CrNiMo17-12-2 (1.4401)
        metalprops.Et = 180*1000;            % N/mm2: Young's modulus, GPa=N/mm2
        metalprops.nyy = 0.3;              % [-]:   Poisson's number
        metalprops.nk = 3.0;                  % [-] nk=3; SFS 2862, 5.1 Kimmoinen lommahdus
(pp.184) (nk for calculating elastic deformation)
        metalprops.sigmal = 220;          % Laskentalujuus, GPa=N/mm2 (calculation  strength)
        metalprops.n = 2;                    % [-] varmuuskerroin (safety factor)
        metalprops.k = 15;                % tube wall thermal conductivity [W/mK]
        metalprops.rho= 8000;                     % material density[kg/m3]
        metalprops.price= 0.65;                 %[€/kg]
        FixedParams.metalprops = metalprops;

    case 3                                 %  X1CrNiMoCuN24-22-8   ( 1.4652 )
        metalprops.Et = 190*1000;            % N/mm2: Young's modulus, GPa=N/mm2
        metalprops.nyy = 0.3;              % [-]:   Poisson's number
        metalprops.nk = 3.0;                  % [-] nk=3; SFS 2862, 5.1 Kimmoinen lommahdus
(pp.184) (nk for calculating elastic deformation)
        metalprops.sigmal = 430;          % Laskentalujuus, GPa=N/mm2 (calculation  strength)
        metalprops.n = 2;                    % [-] varmuuskerroin (safety factor)
        metalprops.k = 11;                % tube wall thermal conductivity [W/mK]
        metalprops.rho= 8000;                % material density[kg/m3]
        metalprops.price= 1;                 %[€/kg]
        FixedParams.metalprops = metalprops;
    case 4                                 %  X2CrNiCuN23-4    ( 1.4655 )
        metalprops.Et = 200*1000;            % N/mm2: Young's modulus, GPa=N/mm2
        metalprops.nyy = 0.3;              % [-]:   Poisson's number
        metalprops.nk = 3.0;                  % [-] nk=3; SFS 2862, 5.1 Kimmoinen lommahdus
(pp.184) (nk for calculating elastic deformation)
        metalprops.sigmal = 410;          % Laskentalujuus, GPa=N/mm2 (calculation  strength)
        metalprops.n = 2;                    % [-] varmuuskerroin (safety factor)
        metalprops.k =  15;                 % tube wall thermal conductivity [W/mK]
        metalprops.rho= 7800;                % material density[kg/m3]
        metalprops.price= 1.5;                  %[€/kg]
        FixedParams.metalprops = metalprops;
end

EconData.interest=0.10;
EconData.years=10;
EconData.r_OM=0.04;
EconData.VAT=0.24;
EconData.fuel_cost=20;
EconData.El_cost=120;
EconData.DH_cost=60;
EconData.fudgefactor=1.0;
FixedParams.EconData = EconData;
end

function [D_OTL, params_ok] = GetDOTL(D_ShIn,HeadType,params_ok)
% Bundle-to-shell clearance data from:
% Sinnott et al.: Chemical Engineering Design, 4th ed. (2005), pp.646, Fig. 12.10
%
% [D_OTL] = m
% [D_ShIn] = m
% [L_bb] = m         *diametrical* clearance, i.e. D_sh - D_OTL, *not* the
%                    distance from shell to bundle!!!!

switch HeadType
    case 'U'     % U-tube
        disp('Error : Cannot calculate U-tube')
        a=0.008;
        b=0.010;
        params_ok = 0;
    case 'L'     % fixed
        a=0.008;
```

```
        b=0.010;
    case 'M'    % fixed
        a=0.008;
        b=0.010;
    case 'S'  % split-ring floating head
        a=0.0445;
        b=0.0275;
        %L_bb = 0.0445 + (0.0275*D_OTL);
    case 'T'  % pull-through floating head
        a=0.0856;
        b=0.0095;
    case 'W'  % outide packed head
        a=0.038;
        b=0.0;
    otherwise
        disp('Error : Unknown head type.')
        a=0;
        b=-2;
        params_ok = 0;
end
D_OTL = (D_ShIn-a)/(1+b);

end

function Fluids = GetFluids()
Fluids.Tci = 25;                    % Inlet T, cold side [K]
Fluids.Thi = 95;                    % Inlet T, hot side [K]
Fluids.Tho = 40;                    % Outlet T, cold side [K]
Fluids.qmc = 68.88;                 % mass flow rate, cold side [kg/s]
Fluids.qmh = 27.78;                 % mass flow rate, hot side [kg/s]
Fluids.pc = 5.0;                    % inlet pressure, cold side [bar]
Fluids.ph = 5.0;                    % inlet pressure, hot side [bar]
% properties according to Mizutani et al., 2003
Fluids.cp_c = 4200;
Fluids.rho_c = 995;
Fluids.my_c = 0.0008;
Fluids.k_c = 0.59;
Fluids.Pr_c = Fluids.cp_c * Fluids.my_c / Fluids.k_c;
Fluids.cp_h = 2840;
Fluids.rho_h = 750;
Fluids.my_h = 0.00034;
Fluids.k_h = 0.190;
Fluids.Pr_h = Fluids.cp_h * Fluids.my_h / Fluids.k_h;
% fouling resistances and conductivities
Fluids.Rt_h = 0.00033;
Fluids.Rt_c = 0.00020;
Fluids.k_fh = Fluids.k_h;
Fluids.k_fc = 0.7;          % Biofouling k = 0.7 W/mK [VDI 2010]
end
```