ON THE SELECTION OF DESIGN METHODOLOGY FOR SHELL-AND-TUBE HEAT EXCHANGERS OPTIMIZATION PROBLEMS

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Abstract.

In the last two decades research on shell-and-tube heat exchangers design has advanced focusing mainly on design optimization problems. While literature focused on applying a wide range of optimization algorithms, the attention to objective function selection has been comparatively scarcer, creating confusion in the designer, who is left without any guideline when undergoing this choice. Literature lacks clarity on reasons for choosing a specific function and authors never justify their choice. This results in equipment configurations which only apparently are optimized but may reveal practical drawbacks or, even, be unfeasible.

As a contribute to fill this gap, in this paper a critical review and comparison of objective functions on a consistent basis is carried out, in order to show their effect on equipment configuration and assess respective merits and drawbacks. It is the first time that this kind of comparative analysis is carried out. Results show that the choice of an objective function strongly impacts on the obtained "optimal" design, that some frequently used functions are counterproductive and may lead to unpractical configurations from the engineering point of view. We show that thermodynamic-based objective functions may not lead to cost-effective design and that, in single-objective optimization, economic functions demonstrate their superiority. We also show that multiple objective optimization may lead to more balanced design and greater flexibility. The novelty and value of this study lies in the awareness coming from this additional knowledge allowing equipment designer and scholars to choose in a more effective manner the objective function to be paired with any optimization algorithm.

Keywords: *heat exchanger optimization, cost functions, objective functions, shell and tube heat exchanger.*

1. INTRODUCTION

Shell and tube heat exchangers (STHE) are widespread in industrial systems representing a critical piece of equipment in many production processes. When used in heat recovery applications, they also contribute to resources conservation. While the basic STHE design procedure is well established, its manual application is time consuming owing to the iterative nature, and relies heavily on designer's subjective choice of parameters values. In order to automate and improve the design process, in the last decades numerical optimization approaches have been applied to STHE design.

While, while some scholars are sceptical about the possibility of adopting precise optimization methods in heat exchanger design [1], an extremely wide range of optimization algorithms has been applied in the literature, as reviewed elsewhere [2-4], and an increasing number of objective functions (OF) have been suggested.

Overall, while the adoption of an optimization algorithm mainly influences the efficiency and effectiveness of the search procedure within the design space, the choice of the OF is relevant, as it dictates the configuration and quality of the resulting "optimal" design. In this respect, the attention to objective function selection has been comparatively scarcer, creating confusion in the designer, who is left without any guideline when undergoing this choice. As a result, one finds many different OFs utilized in the literature, while studies comparing the OFs performances are lacking. Literature lacks clarity on reasons for choosing a specific function and authors never justify their choice, and do not discuss the impact of their choice on the resulting equipment configuration. Moreover, a misleading similarity among some objective functions also increases uncertainty.

Usually, OFs are related either to a cost to be minimized or some technical performance measure to be optimized. However, when using a cost OF the capital investment is often estimated in a crude manner relying on simple parametric functions based on the overall heat exchange surface. This makes them unfit for detailed design as the total exchange area is not responsive to changes in the equipment architecture which impact the manufacturing cost, as discussed by Caputo et al. [5]. On the other side, OF based on physical or thermal performances may lead to equipment configurations which are only apparently optimized, while in practice are affected by practical drawbacks or are simply unfeasible. In fact, many authors do not show nor discuss the actual configuration of the equipment obtained by their choice of OF.

As a contribute to fill this gap, in this paper a critical review and comparison, on a consistent basis, of objective functions is carried out. This is made in order to show their effect on equipment configuration and assess respective merits and drawbacks in order to provide a guidance to equipment designers and improve their awareness when choosing an OF. In greater detail, an attempt is made to answer the following research questions, namely a) is it relevant the choice of an OF when performing optimal design of a STHE?, b) what are the drawbacks of available OFs?, c) how an OF should be chosen?

It is the first time that this kind of comparative analysis is carried out in the literature. The novely and value of this study lies in the practical use of this additional knowledge, as it allows equipment designer and scholars to choose the objective function to be paired with any optimization algorithm in a more effective manner.

The paper is organized as follows. At first a critical literature review is carried out to identify the most frequently used OF in single and multi-objective optimization of heat exchangers. Then six representative OFs, are selected in order to assess their impact on geometric, thermal and economic performances of STHE. A few novel OFs are also introduced by the authors to make the the analysis more comprehensive. A numerical case study is subsequently performed in order to compare the optimized designs obtained with different objective functions in a realistic application under consistent assumptions. The analysis is carried out either using single and multi-objective OFs. Results discussion allows to highlight merits and drawbacks of different OFs also emphasizing their limitations. The necessity of combining thermal with economic performances for the realistic design of equipment is finally highlighted.

2. CRITICAL LITERATURE REVIEW ON OBJECTIVE FUNCTIONS FOR SHELL AND TUBE HEAT EXCHANGERS OPTIMIZATION

To the best of our knowledge, from 2005 to 2021, about 120 research papers centred on STHE optimization appeared in the literature. The time trend shows a progressively increasing number of papers as can be observed in Figure 1, confirming a renewed interest in the topic.

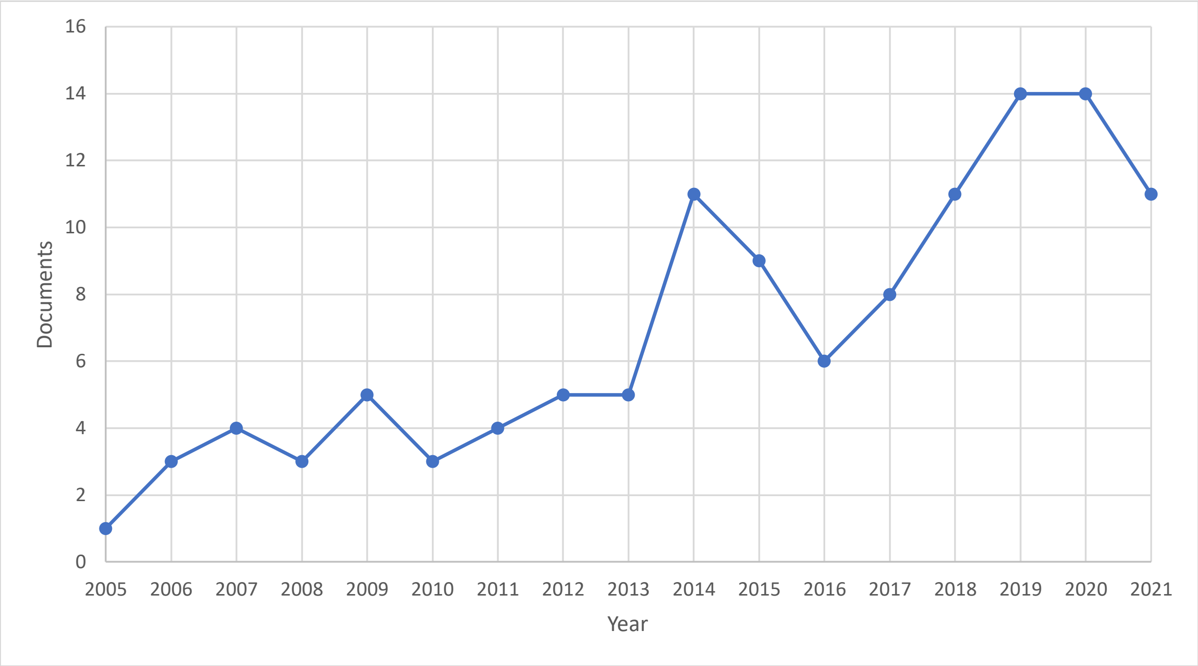

Figure 1 Documents by year focused on shell and tube heat exchanger optimization.

In greater detail, although the design procedure may be reduced to Kern and Bell-Delaware methods, most works deal with mathematical optimization techniques and differ by the adopted numerical method [2].

Table 1 shows a non-exhaustive list with algorithms used in STHEs optimization, with the most used being at the top of the list.

Table 1 Optimization algorithm used in STHE optimization.

Algorithm	***References***
Genetic Algorithm	[4-36]
Non dominated Sorting Genetic Algorithm-II	[37-49]
Particle Swarm Optimization	[16, 24, 47, 50-55]
Multi-Objective Genitic Algorithm	[56-60]
Firefly Algorithm	[19, 22, 61, 62]
Cuckoo Search	[22, 63-65]
Monte Carlo Simulation	[28, 47, 66]
Elitist Jaya Algorithm	[67-69]
Differential Evolution Algorithm	[70, 71]
Heat Transfer Search Algorithm	[72, 73]
Modified Teaching Learing Based Optimization	[74, 75]
Grey Wolf Optimizer	[72, 76]
Symbiotic Organism Search	[72, 77]
Multi-Objective Particle Swarm Optimization	[78, 79]
Passing Veichle Search	[72]
Artificial Forage Optimization	[72]
Salp Swarm Algorithm	[72]
Electro-Search Algorithm	[72]
Grasshopper Optimization Algorithm	[72]
Ant Lion Optimizer	[72]

Alfa Tuning Elephant Herding Optimization	[80]
Differential Evolution Based ABC	[81]
Branch-And-Reduce Optimization Navigator	[82]
DIscrete and Continuous OPTimizer	[82]
Exhaustive Search	[47]
Crow Search algorithm	[47]
Bacteria Foraging Algorithm	[83]
Multi-Objective Self-Adaptive Multi-Population-Jaya algorithm	[84]
Adaptive Range Genetic Algorithm	[85]
Simulated Annealig Algorithm	[33]
Falcon Optimization Algorithm	[86]
Brute Force Algorithm	[28]
Cohort Intelligence	[87]
Delayed Rejection Adaptive Metropolis hasting	[88]
Multi-Objective Heat Transfer Search	[89]
Tsallis Differential Evolution	[90]
Bat Algorithm	[91]
Predator-Prey Algorithm	[46]
Electromagnetism-like Algorithm	[92]
Gravitational Search Algorithm	[93]
Hybrid Particle Swarm Optimization and Ant Colony Optimization	[23]
Distributed Multistart Ant Colony Optimization	[94]
Particle Swarm Local Optimization	[94]
Improved Intelligent Tuned Harmony Search algorithm	[95]
Hybrid Differential Evolution and Ant Colony Optimization	[96]
Biogeography-Based Optimization	[97]
Imperialist Competitive Algorithm	[98]
Quantum Particle Swarm Optimization and Zas Lavskii Chaotic Map Sequences	[99]
Algorithm Of Changes	[100]
Artificial Bee Colony	[101]
Harmony Search Algorithm	[102]
Others	[103-118]
Reviews	[2, 3]

In several cases, superior performances declared by authors for their algorithms are doubtful, in fact results are not fully comparable and not fully discussed. This means that some problem characteristics are not declared, some differences in problem formulation occur or materials and method involved are not consistent [3].

While optimization approaches for STHE design are reviewed elsewhere [2-4], they are not the scope of this paper. This work, instead, is focused on the role of OFs in equipment optimization and on the criteria to properly select an OF to drive a generic optimization procedure.

In fact, while optimization algorithms may be more or less efficient in searching for the optimal solution, it is the OF which determines the nature and quality of the optimal solution. Moreover, advanced optimization algorithms are suited to search efficiently over large design spaces, while in heat exchanger design the feasible design space is somewhat reduced owing to the multiple interdependencies between variables which often can only assume a small number of discrete values, thus preventing to fully exploit the power of advanced optimization algorithms. As a consequence, if the computational advantage of relying on superior search algorithms may often be small in this kind of application, the choice of the OF plays a more relevant role for the practical consequences it bears, and is often the most neglected.

An analysis on keywords appearing in STHE optimization literature has been carried out at first, showing three main classes of OF based on:

- geometric equipment dimensions;
- thermo-fluid-dynamics performances;
- economic performances.

Results are shown in Figure 2 obtained resorting to VOSviewer (https://www.vosviewer.com/) software to analyse Scopus Database data.

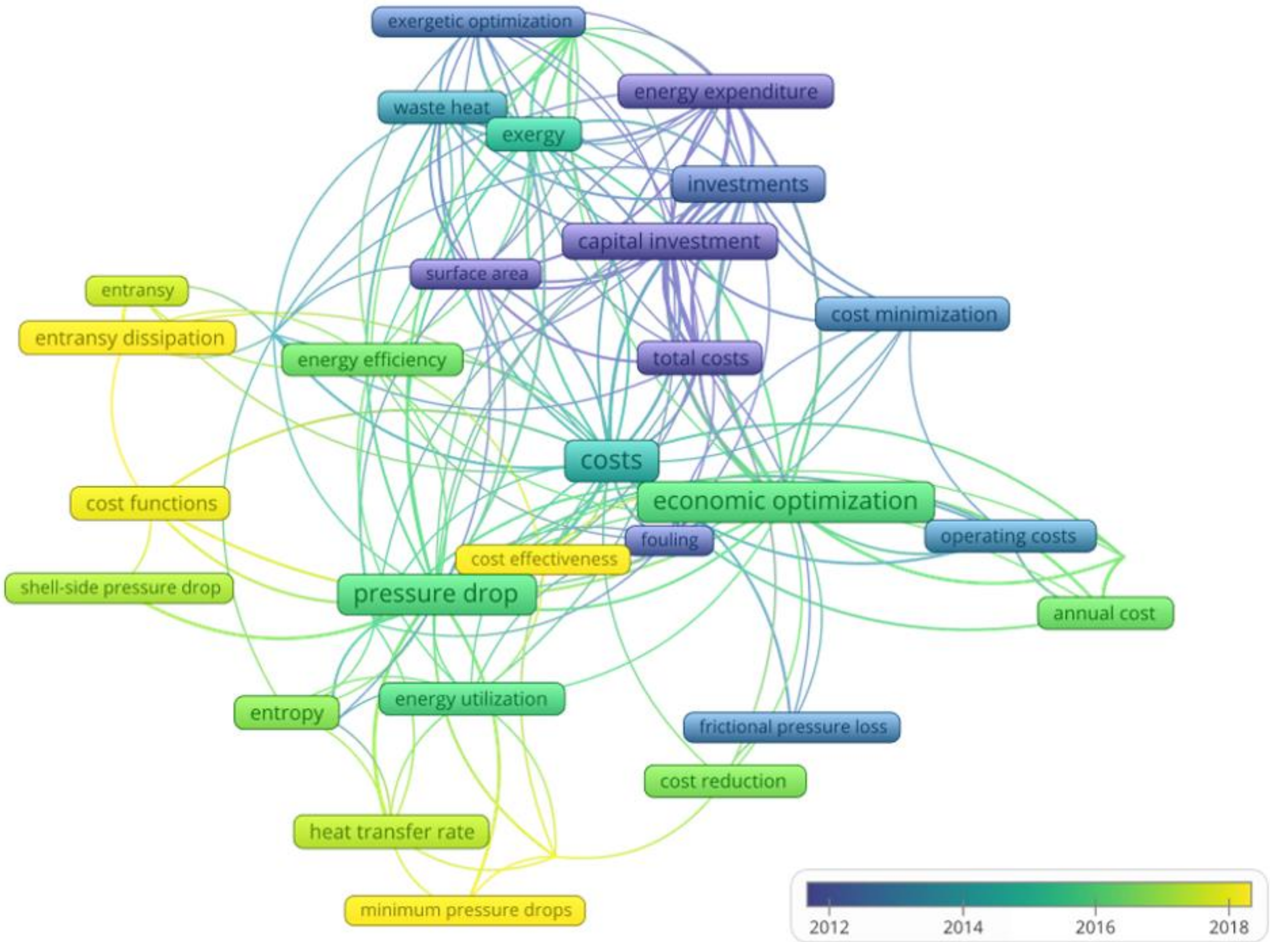

Figure 2 Bibliometric analysis of keywords used in OBJ matters realized processing data with VOSviewer.

Figure 2 offers an overview of OFs used in the literature. In Figure 2 each keyword is represented by a node/label. The bigger the node, more frequent is a keyword in articles. Arcs represent the relationships between keywords, each link means the copresence in a paper. Different colours help to understand the average of publication years of papers which include the keyword.

In greater detail, most frequently adopted objective function is costs, in wide sense, but also heat transfer area, pressure drop, energy disruption, exergy, entropy, ensergy and heat transfer rate have been used. Recent studies focus on multi-objective optimisation, in order to combine thermal and economic performance, cost and effectiveness are optimised simultaneously. In last decades the minimisation of pressure drop has become crucial in order to introduce new geometric configurations of baffles enabling the growth of the overall heat transfer rate but, on the other hand, also increasing the required pumping power. Minimisation of energy dissipation has also been used, but some articles have shown that the mathematical formulation is not able to produce practical architectures. Cost-oriented objective functions are widely used in literature for sake of comparison among optimisation algorithms. These kind of OF has a usual formulation and rarely a more detailed model has been used to evaluate investment and operating cost.

Table 2 reports a non-exhaustive list containing OFs and the number of occurrences in single and multi-objective problems.

Table 2 Number of times of occurrence of OFs in literature in single and multi-objective optimization.

	Number of occurence		
OF	**Single-OF**	**Multi-OF**	**TOT**
Total cost	52	15	67
Total annual cost	10	7	17
Investment cost	1	1	2
Operating cost	0	1	1
Area	6	5	11
Weight	1	0	1
Effectiveness	2	10	12
Heat Transfer rate	1	11	12
Pressure drop	1	15	16
Exergy disruption	1	5	6
Entropy generation unit	2	2	4
Fouling resistance	1	1	2
Entransy	2	2	4
Global heat transfer coefficient	0	1	1

In single-objective optimization of STHE, four different clusters can be identified as discussed in the following:

1. geometric functions;
2. fluid-dynamic and energy-related functions;
3. weighted average of different performances measures;
4. cost functions.

Moreover, multi-objective functions may be also found, combining, for example, costs and thermal effectiveness.

This clustering is important to identify OFs which can be utilized stand-alone and others which should be only used in conjunction with other OFs in a multiple-objective setting. In fact, only some OFs directly or indirectly consider some design aspects which lead to a useful, practical, and realistic configuration.

2.1. Single-objective optimization of shell and tube heat exchangers

2.1.1. Geometric functions

Geometric equipment dimensions have some interesting practical implication (e.g. in costs, transportation, arrangement of equipment within densely packed plants etc.) and literature gave importance to their optimization [4, 30, 71, 82, 103, 104, 106, 118]. However, the search for equipment compactness is often a proxy for indirectly reducing cost. The typical geometric parameter to be minimized is the overall heat transfer area, whereas in one work weight was considered [4]. Some authors aimed at heat transfer surface minimization constrained to an heat transfer rate, using different meta-heuristic algorithms [71, 104], or resorting to Taguchi design approach [30] and to Mixed Integer Linear Programming (MILP)[106]. Yang et. al examined different strategies for heat transfer enhancement with the aim to reduce equipment surface area and Investment Cost (IC) [82, 118]. However, small surface area usually means small tube diameter and short length, leading to large pressure drop, which increases operating costs (OC). Small Total Cost (TC) inevitably results from a trade-off between IC and OC. This is shown in [103] where surface area and Total Annual Cost (TAC) were compared as the OF of a MILP.

2.1.2. Fluid-dynamic and energy-related functions

This type of functions is adopted for instance in the following references [11, 13, 19, 22, 26, 29, 35, 61, 107, 110, 119, 120].

A number of different thermal-performance measures have been considered, i.e. exergy, efficiency, entropy generation, entransy dissipation and effectiveness. In general, it has to be pointed out that energy-related performances are more linked to the values of process parameters (i.e. input and output temperatures) than to the actual geometry of the equipment. Therefore, it is not advisable to use such kind of performances as the sole OF because they do not help in equipment design. In fact, either a multiplicity of alternative configurations (not equivalent from the point of view of other relevant characteristics) may share the same value of the thermal performance, or an unfeasible or economically unsustainable geometrical configuration could result when trying to optimize an energy-related performance only.

Entropy generation number was introduced by Bejan [119] and it seemed immediately interesting as a possible OF for STHEs also accounting for pumping power reduction. However, several authors pointed out that to minimize entropy generation does not necessarily maximize thermal efficiency. The so called “entropy generation paradox” implies that economic savings coming from reduction of irreversibility are compensated by higher costs caused by lower thermal efficiency. To avoid this paradox other authors [13] used a different entropy generation number formulation. Recently it was demonstrated that the most significant effect of entropy generation minimization was on pressure drop and not on heat loss [61].

Guo et. al explored the link between thermo-economical performances and shell-side field synergy number [11]. Exergy destruction cost is also considered and integrated with TC introducing exergetic cost minimization [35, 107]. A more recent thermodynamic function useful for heat exchanger optimization is entransy [120]. It represents the ability to transfer heat and while reducing its dissipation thus preserving the reversibility of the transformation. It was used with number of entransy dissipation [29] and with entransy dissipation resistance [26] minimization.

On the other side, Effectiveness optimization promises to maximize value by exploiting all thermal energy of both fluids [19, 22], but the final configuration of the equipment could be unacceptable from either the surface requirements and economic performances. In fact, to maximize effectiveness means to bring the exchanged heat as nearest as possible to the maximum exchangeable heat quantity, which is not always advisable or feasible from a practical point of view. For instance, in some configurations, i.e. counter-current design, this can implies that the hot fluid outlet temperature is lower than the outlet temperature of the cold stream. This requires an unacceptable amount of heat transfer area and consequent pressure losses.

Fouling resistance is also a well-known problem of STHE, and the geometry of equipment significantly influences the evolution of fouling film. Putting heat duty and pressure drop as constraints, a mixed integer linear programming problem for the minimization of fouling resistance was proposed. Shell-side fouling resistance was reduced by 17% meanwhile tube-side by 48% compared with literature-available designs [110].

2.1.3. Weighted average of multiple performance measures (WAMPM)

Some authors combine different objectives in a single function with the introduction of their weighted sum (e.g. [28, 47, 66]). Please note that this kind of approach is substantially different from using a multiple objective OF. In fact, the WAMPM method identifies a single optimal solution, while multiple-objective methods usually generate a Pareto optimality frontier and require specific solution algorithms. In WAMPM a nondimensionalization of the single performance measures is required in order to optimize a single compound performance indicator. The disadvantage is that the OF and its value no longer has a physical meaning and is unrelated to the equipment configuration or its functionality. Any connection between the optimized performance and physical characteristics of the exchanger is lost. WAMPM approach was used with different OFs, but more recently it was adopted to optimize equipment sustainability [66]. Social, environmental and economic sustainability was optimized considering impact on labour force, carbon plant, costs and others KPIs with different metaheuristic algorithms [28] or to better manage the project sustainability [47]. However, the problem of impacts evaluation, and weights selection is still under investigation.

2.1.4. Cost functions

Cost functions are the most frequent in STHEs optimization problems statement [5, 6, 8, 10, 12, 14-16, 18, 21, 23-25, 50, 52-54, 62-65, 67, 69, 70, 72, 73, 76-78, 80, 81, 83, 85-88, 90, 92-102, 105, 108, 114, 116, 117]. Mainly two sets of cost-related OFs can be found, namely Total Cost and Total Annual Cost. In both cases either capital investment and operating costs (often limited to pumping costs) are factored in, thus requiring some type of discounting or levelizing of cash flows. Minimization of investment cost, as discussed above, is instead pursued through surface area minimization.

In a first paper [116] authors optimized the STHE using TAC, considering pumping power and thermal loss to evaluate OC. IC was computed, as frequently happens, resorting to Hall's method, where the capital investment is expressed as $IC = a_1 + a_2\ A^{a3}$ being A the heat transfer area. Coefficients (a_1, a_2, a_3) depend on surface range, the relevance of scale economy, and the HE construction material and type. In this respect it must be noticed that the above formulation of IC only considers the heat overall exchanger surface, totally neglecting the actual geometrical configuration of the equipment. In fact, the same area could be obtained with several sets of geometrical parameters values leading to different values of manufacturing cost. To cope with this problem Caputo et. al [5] introduced a detailed analytical cost estimation for STHEs considering actual manufacturing processes and geometrical parameters values.

Some authors include both the capital investment of the exchanger and the pumps, whose size depend, in turn, from the exchanger pressure losses [67, 96]. One paper [117] included even exergy production cost in OC computation. Selbaş et al. [6] include maintenance cost with an annual percentage increment of OC, whereas others [8] resize the heat exchange surface in order to reduce the effect of fouling factors, and model IC also adopting the Purohit expression [12]. In paper [88] a more complete formulation of cost is adopted by including indirect manufacturing cost. Global sensitivity analysis (GSA) was also explored [102] in order to identify the design variables most influential on costs, before attempting an optimization procedure in order to reduce the computational complexity. In paper [72] and [114] different optimization algorithms are compared on a consistent basis assuming a total cost based objective function.

Previous papers, as said in the introduction, used generally Kern and Bell-Delaware method for STHE sizing, but other authors used constructal theory [14, 18, 21] and another one a non-traditional optimization modifying existing methods [108]. A focus on shell and double concentric tubes heat exchanger optimization was proposed [25]. Maintenance and reliability considerations are often made [69], e.g. restraining a coefficient of increase of surface into a given interval [73], but an analytical formulation for the optimization of maintenance schedule is available only in one paper [15]. In [64] a constraint on the effectiveness is introduced when minimizing TC. Other authors [65] included in problem some penalties in TC assessment when some threshold performance values, such as a minimum value of effectiveness, were not met. The TC was increased linearly with the level amount of constraint violation. This means that solutions not meeting some constraints are not merely discarded but are only penalized.

Another TC mathematical formulation for compact STHEs was proposed, and uncertainty of correlations and inlet quantities was included: the best HE was chosen resorting to multi-criteria decision making under uncertainty [78].

2.1.5. Constraints selection

Whichever the objective function chosen, it also needs suitable constraints. Design correlations have their own ranges of validity, not always accurately respected [3]. Moreover, it is crucial to use constraints which ensure to obtain a reasonably feasible equipment configuration. Nature and number of constraints depend on the chosen objective function. For instance, if there is not a specific requirement on maximum allowable pressure drop and the objective function under investigation is the total cost, it is possible to neglect an explicit constraint on pressure drop. In contrast, if the objective function is the minimization of heat transfer area, that constraint must be considered to avoid an excessive pressure drop.

Sometimes, in literature there is a lack, or poor definition, of suitable constraints preventing to obtain unfeasible or unrealistic heat exchanger architectures (e.g. obtaining the best effectiveness but a huge heat exchange surface).

In some cases, not all constraints are expressed via equations and the solution is tuned once the algorithms finds a theoretical solution optimum, even if this implies reaching a sub-optimal (but more feasible) solution. However, to properly explicit constraints in analytical manner may not be easy, and the choice of constraints may influence the choice of the optimization algorithm or vice versa. In fact, an incompatibility may occur between algorithm and constraints, forcing to adapt the constraints to the algorithm or to neglect some constraint.

An alternative approach may be the use of multi-objective optimization formulations, looking at a set of equipment performances and achieving non dominated solutions. In this case the difficulty is transferred to choosing one solution among the obtained configurations.

2.2. Multi-objective optimization of shell and tube heat exchangers

Multi-objective optimization (MOO) is largely explored in STHEs field, even if many papers are more focused on MOO algorithms performances, than on the OFs selection and justification. However, this kind of approach plays a key-role in simultaneous optimization of the trade-off implied by economic and thermal performances [38, 43, 68, 74, 79, 91], when a single OF can be misleading or useless for equipment design. This gives decision makers the possibility to select the preferred configuration on the Pareto efficient frontier representing the set of non-dominated solutions without incur in sub-optimal designs.

In fact, as previously mentioned, thermal effectiveness maximization causes a rapid increase in TC owing to an increase in the surface area, driven by the simultaneous reduction of the Logarithmic Mean Temperature Difference (LMTD), as the outlet temperatures of fluids should be about the same, and of the LMTD correction factor which, below the 0.8 threshold, rapidly falls and becomes uncertain.

Exergy efficiency is also used instead of effectiveness [39] obtaining similar results. A first MOO attempt with a formulation of exergetic cost was made by Ozcelik [9]. In double OFs optimization exergy efficiency, resorting to exergy disruption [42], and entransy dissipation theory was used with TAC [48]. Effectiveness, TC, pressure drop and entropy generation units were optimized simultaneously [89] to understand the importance of reducing the effect of the irreversible transformation from friction and heat transfer points of view.

Heat transfer rate (Q) maximization and TC minimization were often considered [17, 55, 58]. Q and pressure drop were also correlated using Computational Fluid Dynamics simulation with Taguchi experimental design [109] and Artificial Neural Network (ANN) [27, 31, 36] for different STHEs in terms of baffles types, such as segmental, helical and disc and doughnut [41]. Helical baffle and coiled wire insert technology [32], the adding of nanofluid [56] and segmental porous baffles were also explored with GA-ANN [34] and Multi-Objective Genetic Algorithm (MOGA) [57] for Q enhancement.

Since fluids velocities influence global heat transfer rate and pressure drop creating a trade-off, the Pareto frontier is very useful in order to choose the best solution [59]. Application of response surface method and MOGA were demonstrated as very useful in increasing thermal performance, i.e. shell-side Nusselt number, and decreasing friction loss in STHEs with fold baffles for the elimination of triangular leakage zones between adjacent baffles [60].

TC could be optimized resorting to MOO problem including both IC and OC as an objective [45]. The widespread use of Hall correlation, nevertheless, limits the IC estimation accuracy in the computation of equipment area and of OC in pressure drop evaluation. For this reason, it is possible to optimize another formulation that cope with the cost coefficients selection uncertainty minimizing simultaneously exchange area and pressure drop [40, 46, 113]. Other consideration on equipment surface and TAC can be found in Elsays et al [51].

Ecological impact optimization was considered for MOO too with the minimization of TC and the entransy dissipation, in order to exploit the whole thermal energy of the fluids and reduce pumping energy consumption [49]. From a similar perspective, but allowing for maintenance consideration, energy efficiency and fouling rate help were studied with ANN [111].

Agarwal and Gupta [37] optimized TAC and mass flow rate of service fluid, considering a case where outlet cooling water, after its passage in STHE, was recycled in a cooling tower. The reduction of water consumption is very important not only for its economic value but also for its availability concern.

Finally, Lambert and Gosselin [20] considered epistemic uncertainty and minimized simultaneously the TAC and its standard deviation. This approach is very important to understand the influence of uncertainty on the equipment design and it is not fully explored yet for STHEs design.

Overall, multi-criteria decision making techniques can help in choosing the weights in the OF for the selection of the best equipment configuration according to user preferences. A MOO software tool of STHEs was also developed in [75].

From the above discussion the following issues may be pointed out.

The large number of alternatives shows that a consensus in the research community toward a standardization of OFs has not been reached yet. Unfortunately, most authors do not motivate their choice, even if they adopt well-known or recently developed OFs.

Cost-related OFs are most frequent, but even energy-related OFs occur, especially in MOO problems.

In some case, the obtained optimal design seems to be unfeasible or non-realistic (e.g., HE with huge surface area or excessive total cost). This explains why some author is sceptical on literature results [1].

In general, while some types of OFs, such as cost or geometry, have a direct meaning as far as design or operational aspects are concerned, energy-related OFs do not define a specific equipment configuration and can be misleading if the goal is to reach a “good” design of the equipment. In fact, a multitude of different exchangers could be defined having the same energy-related performance measure, and a good thermal effectiveness performance does not necessarily imply an equally good performance under other aspects. Energy-related performance measures are mainly aimed at optimizing process parameters and can be computed regardless of the geometric configuration of the equipment. Therefore, while the former may be used as stand-alone OFs, the latter are better paired to other OF in multiple objective design instances.

Cost performance measures although being linked to a performance having a direct practical implications, indirectly express either geometric and thermal performances. For instance, a low total cost equipment has a geometry reducing the surface area while preserving the heat transfer efficiency (transferred heat per unit area) and pressure losses. Therefore, it simultaneously optimized several categories of design goals. Multiple-objective OFs respond to two different requirements, i.e. the legitimate necessity of optimizing simultaneously two or more performance measures, and the need to obtain an effective and feasible geometrical design even when adopting non geometry-related performance measures such as the energy-related ones which would be consistent with an indefinite set of alternative geometrical designs.

3. RESEARCH METHODOLOGY

The literature review showed that the OF selection for heat exchanger design optimization is a sensitive although often neglected matter, and that while STHEs optimization can have different objectives, it should always be kept in mind that the ultimate scope of HE is heat transfer to be obtained with a good engineering design of the equipment.

To better clarify previous statements, and to assess the implications on design of the OF choice, optimal equipment configurations resulting by adopting different OFs will be compared in a consistent manner. At first single-objective optimization is carried on, and MOO is subsequently considered. For optimizations purposes, the Matlab library of GA and MOGA algorithms is used to perform computations, together with the design procedure described in [10].

3.1. Selection of single-objective functions for shell and tube heat exchangers design comparison

In order to provide an extensive comparison, eight OFs were chosen representing both geometric, thermal and economic objectives. In particular, to better characterize geometric issues three novel objective function have been proposed by the authors (OF2-3-4) whereas are taken from the literature as indicate below.

3.1.1 Geometric OFs

Four OFs were selected in order to pursue equipment compactness. The first one (Eq. 1) is also related to *IC* minimization, while the remaining three aim at space saving in industrial plants and have not been considered previously in the literature.

OF1: Heat transfer area *A*

$$\min(A) = Nt\pi d_o L \tag{1}$$

This is a traditional OF widely adopted in the literature. *A* reduction leads to compact heat exchanger. Compactness is one of the most required characteristics and it is strictly related to lower *IC*.

OF2: Area Footprint *AFP*

$$\min(AFP) = LD_s \tag{2}$$

This represents the rectangular ground footprint of the equipment and is a measure of land occupation in an industrial plant. The occupied area is considered as the tubes length *L* times the shell diameter D_s, and could represent an opportunity cost.

OF3: Tubes length *L*

This is merely an OF trying to reduce the equipment size by shortening its tubes length (min(L)).

OF4: Volume Footprint *VFP*

$$\min(VFP) = \frac{\pi {D_s}^2}{4} L \tag{3}$$

This is the same as *AFP* but extended to the equipment volume, to be used when available volumetric space represents at the same time a constraint and an opportunity cost.

3.1.2 Energy-related OFs

OF5: Pumping power *P*

$$\min(P) = \left(\frac{1}{\eta}\right) \cdot \left[\left(\frac{m_t}{\rho_t}\right) \cdot \Delta P_t + \left(\frac{m_s}{\rho_s}\right) \cdot \Delta P_s\right] \tag{4}$$

where η is the pump efficiency and ρ_T and ρ_S are respectively the density of tube side fluid and shell side fluid.

This is an OF related to a fluid dynamics perspective. The importance of its minimization resides on its effect on pressure drop both shell side (ΔP_s) and tube side (ΔPt). Pressure drop minimization also influences pump sizing and operating cost from a practical point of view.

From thermal perspective, instead, effectiveness (ε, Eq. 5 [121]) and number of entransy dissipation unit (g, Eq. 6 [29]) are used. In literature is shown that g could be optimized in two different ways, with constant Q and so optimizing the mass flow rate or outlet temperature of service fluid and computing the other from the energy balance or resorting to ε-NTU method [122] for sizing the STHE, whereas ε with only the latter. The first manner for g optimization is not a real optimization because when Q is constant, the thermal performance of the HE remains the same and only pressure drops are optimized. In this case the optimization algorithm merely the outlet service fluid temperature equal to outlet process fluid temperature, reaching a value of g near 0.5. In addition, pressure drop contribute to g is of about three orders of magnitude less than the thermal contribution and so the OF is not much sensitive to frictional loss.

<u>OF6: Heat exchanger effectiveness ε</u>

$$\max(\varepsilon) = \frac{2}{(1+C^*)+(1+C^{*2})^{1/2}\coth\left(\frac{NTU}{2}(1+C^{*2})^{1/2}\right)} \tag{5}$$

where Number of Thermal Units (NTU) is the product of HE surface and global heat transfer coefficient divided by the smallest of the two fluids stream heat capacity rates, while C^* is simply the ratio of the smaller to larger heat capacity rate.

<u>OF7: Number of entransy dissipation unit g</u>

$$\min(g) = g_{\Delta T} + g_{\Delta P} = \frac{\frac{1}{2}(mc_p)_h(t_{h,i}{}^2-t_{h,o}{}^2)+\frac{1}{2}(mc_p)_c(t_{c,i}{}^2-t_{c,o}{}^2)+m_h\frac{\Delta P_h}{\rho_h}\frac{(t_{h,o}-t_{h,i})}{\ln\left(\frac{t_{h,o}}{t_{h,i}}\right)}+m_c\frac{\Delta P_c}{\rho_c}\frac{(t_{c,o}-t_{c,i})}{\ln\left(\frac{t_{c,o}}{t_{c,i}}\right)}}{Q(t_{h,i}-t_{c,i})} \tag{6}$$

Where $g_{\Delta T}$ is the thermal dissipation contribution and $g_{\Delta P}$ the fluid-dynamic dissipation contribution. m and c_p are mass flow rate and specific heat respectively of hot fluid (h) and cold fluid (c). Q is the heat transfer rate, whereas t represents temperatures: subscript i identifies inlet, o outlet, c and h cold and hot fluids.

3.1.3 Economic OFs

From an economic point of view the selected objective function is *TC*. The total discounted HE cost is computed as sum of investment cost (Eq. 8), resorting to Hall correlation, and present worth of pumping cost (*DOC*, Eq. 9).

<u>OF8: Total cost *TC*</u>

$$\min(TC) = IC + DOC \tag{7}$$

$$IC = a_1 + a_2 S^{a3} \tag{8}$$

$$DOC = \sum_{N=1}^{Ny} \frac{P}{(1+i)^n} \cdot Cen \cdot H \tag{9}$$

Economic values and parameters for cost evaluation are shown in Table 3. For symbols meaning please refer to the nomenclature at the end of the paper.

Table 3 Parameters used to assess the investment and operating costs.

a_1	a_2	a_3	η	H (h/y)	i (%/y)	Ny (y)	Cen (€/kWh)
8000	259.2	0.91	0.7	7000	10	10	0.12

3.2. Selection of multi-objective functions for shell and tube heat exchangers design comparison

In case of MOO the following OFs are used,

OF1 = Heat transfer area *A* and Total Cost *TC*
OF2 = Area footprint *AFP* and Total Cost *TC*
OF3 = Thermal effectiveness ε and Total Cost *TC*

The analysis of multi-objective optimisation is not carried out to introduce a new optimisation method or new objective functions, but to compare different combinations of objective functions on a consistent basis and to emphasise the effect of combining several objective functions in comparison with using them stand-alone. Whereas OF1 may be found in [51] and OF3 are widely used in the literature ([38, 43, 44, 74, 75, 79, 91]), AFP, namely OF2, is a new objective function introduced by the authors, the combination with total cost should be considered as a new formulation.

3.3. Reference case description

In order to compare in a consistent manner the equipment configurations resulting from the above objective functions the Kern method [123] for HE sizing is used in a reference application case. Exception is made for OF7 and OF8 where the ε-NTU design method is utilized.
In this manner the outlet temperatures of fluids are computed and only inlet temperatures and mass flow rates are assigned. Moreover, we assume that heat exchanger must be designed to cool a process fluid, and nominal flow rates, temperatures and thermophysical properties of both fluids are as shown in Table 4. Obviously, outlet temperatures must not to be considered when ε-NTU method is used.

Table 4 Nominal conditions and thermophysical properties of the two fluids.

Fluid	m (kg/s)	t_i (°C)	t_o (°C)	ρ (kg/m3)	c_p (kJ/kgK)	μ (Pa s)	λ (W/m K)	Rf(m^2 K/W)
methanol	27.8	95	40	750	2.84	0.00034	0.19	0.0002
sea water	68.9	27.5	40	995	4.2	0.0008	0.59	0.00033

Considered design and optimization variables are shell diameter (D_s), baffles spacing (B), tubes diameter (d_o), number of tube-side passages (n), tube-side fluid and tubes pattern for Kern method, while tubes length (L) is also included for ε-NTU method. Problem constraints include maximum allowable pressure drop of 70 kPa, length to shell diameter ratio in range 3-15, tube-side and shell-side fluid velocity respectively in range 0.6-2.5 m/s and 0.4-1.5 m/s. Latter two lower bounds are introduced to reduce fouling effect.

3.4 Comparison methodology

In order to compare different optimal designs obtained by the optimization of previous OFs,

Each STHE will be optimized referring to a j-th OF (j=1…8) and will be evaluated respect to eight performances *p* - namely *A, AFP, L, VFP, P, ε, g, TC* - identified by subscript *i*=1…8.
Then a relative performance index I_{ij} (Eq. 10) is introduced, measuring the relative difference between the value of *p* assumed from the *j*-th design and its optimum value

$$I_{ij} = \frac{p_{ij} - p_{ii}}{p_{ii}} \tag{10}$$

being p_{ij} is the *i*-th performance value in case of optimization respect to *j*-th OF, whereas p_{ii} is the performance value of an equipment optimized precisely for that performance.

4. RESULTS DISCUSSION

4.1 Single objective optimization results

At first, single-objective optimization results are considered. Resulting optimal equipment configuration are show in Table 5, while

Table **6** shows the corresponding equipment performances, and Table 7 shows the value of the index I_{ij}. In the Tables each column is associated to a distinct *j-th* OF, namely *A, AFP, L, VFP, P, ε, g, TC*.

Table 5 Optimized shell and tube heat exchanger configuration.

OF	*A*	*AFP*	*L*	*VFP*	*P*	*ε*	*g*	*TC*
D_s	0.7	0.8	0.8	0.8	1.0	1.2	1.4	0.9
L	4.3	2.4	2.4	2.6	4.3	10.0	9.1	2.7
B	0.5	0.5	0.5	0.5	0.4	0.7	0.5	0.9
n	4	6	6	6	2	8	8	4
d_o	0.012	0.012	0.012	0.012	0.02	0.012	0.022	0.012
Pattern	Square	Triang	Triang	Triang	Square	Triang	Triang	Square
Tube side	Methanol	Methanol	Methanol	Methanol	Water	Methanol	Methanol	Methanol
Pt	0.015	0.015	0.015	0.015	0.025	0.015	0.0275	0.015
Cl	0.003	0.003	0.003	0.003	0.005	0.003	0.006	0.003
Nt	1116	2085	2086	1873	1148	6828	2032	2311
v_t	1.84	1.47	1.47	1.64	0.60	0.60	0.60	0.89
Re_t	38871	31202	31187	3474	11941	12706	23294	18772
Pr_t	5.1	5.1	5.1	5.1	5.7	5.1	5.1	5.1
h_t	4314	3619	3617	3944	3248	1764	1562	2410
ΔP_t	69996	47656	47619	61046	4302	37427	18381	13503
D_e	0.012	0.009	0.009	0.009	0.020	0.009	0.016	0.012
v_s	0.96	0.93	0.92	0.93	0.40	0.42	0.50	0.43
Re_s	14249	10004	9932	10006	17461	4493	9795	6331
Pr_s	5.7	5.7	5.7	5.7	5.1	5.7	5.7	5.7
h_s	6152	6931	6904	6932	1280	4463	3737	3937
ΔP_s	69999	69990	68604	69998	10209	70000	70000	8044
U	969	935	934	960	562	661	607	739
S	179	186	186	181	309	2574	1280	235
IC	37130	38089	38107	37359	55797	337078	182300	45253
OC	8932	7937	7820	8534	811	7479	6632	1269
DOC	54885	48774	48056	52438	4987	45960	40754	7799
TC	92015	86863	86163	89797	60784	383038	223054	53052
ε	0.79	0.79	0.79	0.79	0.79	0.87	0.87	0.79
$t_{h,o}$	40.0	40.0	40.0	40.0	40.0	34.4	34.4	40.0
$t_{c,o}$	40.0	40.0	40.0	40.0	40.0	41.5	41.5	40.0
g	0.5011	0.5007	0.5007	0.5009	0.5001	0.4493	0.4491	0.5002
$g_{\Delta P}$	0.0011	0.0007	0.0007	0.0009	0.0001	0.0005	0.0002	0.0002

$g_{\Delta T}$	0.5000	0.5000	0.5000	0.5000	0.5000	0.4488	0.4489	0.5000
AFP	2.83	1.86	1.86	1.94	4.48	11.98	12.66	2.42
VFP	1.47	1.15	1.15	1.15	3.68	11.26	13.80	1.71
P	10.6	9.4	9.3	10.2	1.0	8.9	7.9	1.5

Table 6 Performance values for each optimized design.

		Objective function (j)							
		A	*AFP*	*L*	*VFP*	*P*	*ε*	*g*	*TC*
Performance (i)	*A*	179	186	186	181	309	2574	1280	235
	AFP	2.83	1.86	1.86	1.94	4.48	11.98	12.66	2.42
	L	4.3	2.4	2.4	2.6	4.3	10.0	9.1	2.7
	VFP	1.47	1.15	1.15	1.15	3.68	11.26	13.80	1.71
	P	10.6	9.4	9.3	10.2	1.0	8.9	7.9	1.5
	ε	0.79	0.79	0.79	0.79	0.79	0.87	0.87	0.79
	g	0.5011	0.5007	0.5007	0.5009	0.5001	0.4493	0.4491	0.5002
	TC	92015	86863	86163	89797	60784	383038	223054	53052

Table 7 Indexes I_{ij} values for different OF and performance measure.

		Objective function (j)							
		A	*AFP*	*L*	*VFP*	*P*	*ε*	*g*	*TC*
Performance (i)	*A*	0.00	0.04	0.04	0.01	0.72	13.36	6.14	0.31
	AFP	0.52	0.00	0.00	0.04	1.41	5.44	5.80	0.30
	L	0.80	0.00	0.00	0.08	0.81	3.23	2.86	0.14
	VFP	0.28	0.00	0.00	0.00	2.20	8.79	11.00	0.49
	P	10.00	8.78	8.63	9.51	0.00	8.22	7.18	0.56
	ε	0.09	0.09	0.09	0.09	0.09	0.00	0.00	0.09
	g	0.12	0.11	0.11	0.12	0.11	0.00	0.00	0.11
	TC	0.73	0.64	0.62	0.69	0.15	6.22	3.20	0.00

The substantial differences of optimal configurations give evidence of the importance of OF selection.

Looking at table 5, it is straightforward that each adopted OF minimizes (or maximizes, if is it the case) the performance included in OF formulation. For sake of example, using *A* as OF it is possible to find that heat exchange surface reaches the minimum value but such objective function (like *AFP*, *L* and *VFP*) neglects operating cost. For this reason, pressure drop, on tube and/or shell side, is close to maximum allowable value of 70 kPa.

Using *P* as OF the other heat exchanger performances are neglected, giving minimum values for pumping power, on both sides, but at the same time, values of surface *A*, equipment footprint *AFP*, equipment length *L* and volume footprint *VFP* bigger than the minimum values.

OFs *ε* and *g* lead to equipment having heat exchange surface and investment cost an order of magnitude bigger than others OFs and, at the same time, high values of pressure drop.

Figure 3 summarizes I_{ij} values resorting to spider plots, highlighting the relative performances of optimal design configurations respect all selected performance measures. In particular, each graphic of Figure 3 refers to a specific *j-th* OF, and the plotted points depict the corresponding I_{ij} index values showing the relative performance of that optimal exchanger as compared to the corresponding performance of a HE optimized for each *i-th* performance measure. Obviously, a hypothetical HE having the best performance in all the considered performance measures would have a spider plot where all points would collapse at the origin of the graph.

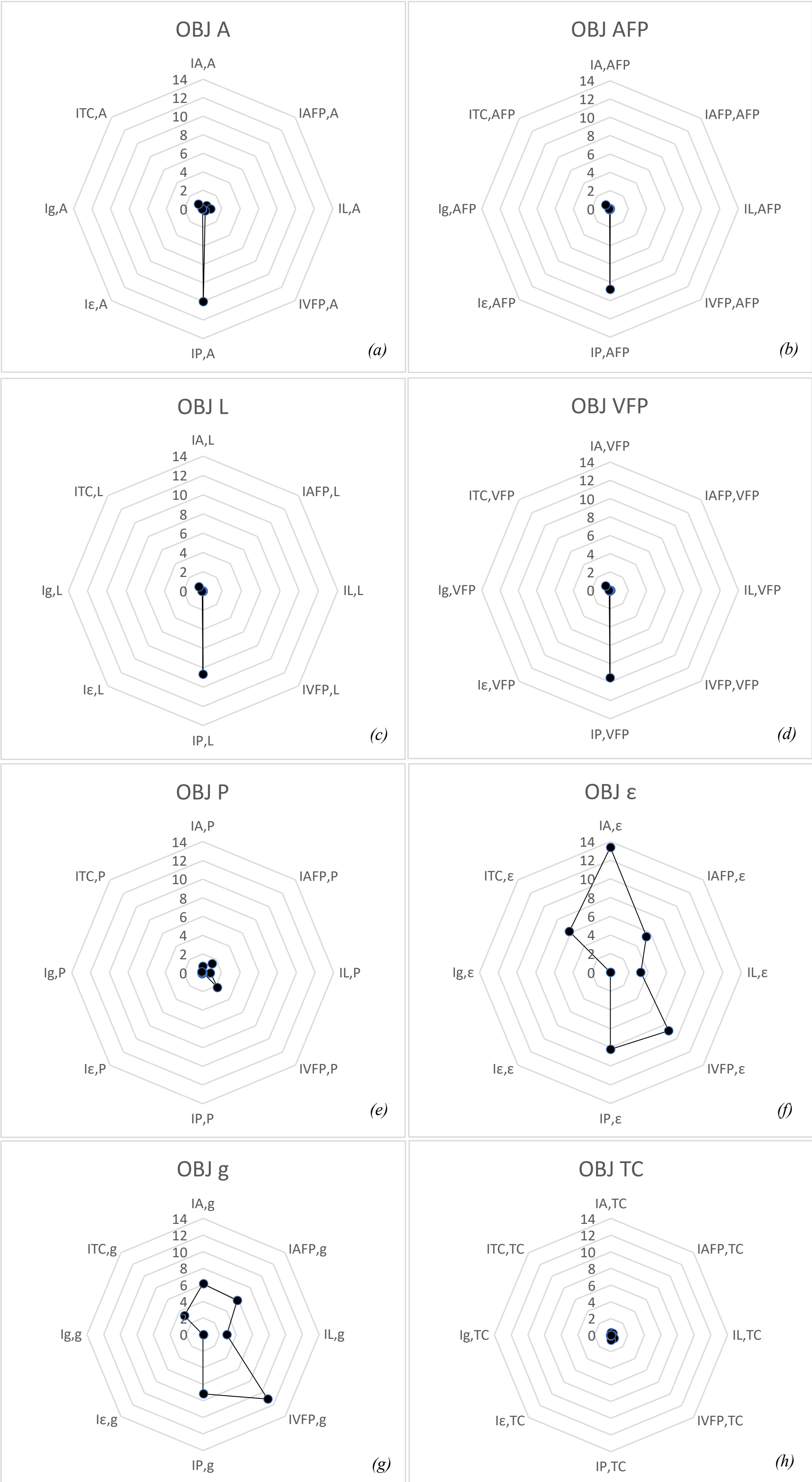

Figure 3 STHE design performances comparison.

Graphs 3a to 3d show very well that geometric optimization, being not sensitive to pressure drop, leads to a consistent increase of pumping power. *P* increases of about 10 times in comparison to *P*-optimized design. Passing to this latter case (Fig. 3e), as *P* influences directly *OC* and the geometry of HE, then *TC* is "only" about two times bigger than *TC*-optimized one, and in general P-optimized configurations are quite good overall performance measures

Effectiveness maximization leads to a configuration affected by noticeable degradation in all other performance measures (Fig. 3f). STHE surface increases 14 times if compared to *A*-optimized HE and even pumping power and *TC* grow up. Heat exchange area increases because the hot fluid outlet temperature is kept lower than cold fluid outlet temperature in order to exploit the whole thermal power of fluids, so corrective factor of *LMTD* falls under the 0.8 threshold.

In case of Number of entransy dissipation units (Fig 3g) the above considerations are confirmed by experimental results. Outlet temperature are the same of ε-optimized design, so from thermal point of view effectiveness was maximized. Pressure drop is contained by $g_{\Delta P}$, but it is three order of magnitude minor than $g_{\Delta T}$, and the final effect is that g is not too sensitive to its contribution.

Very often researchers have exempted themselves from showing the final HE configuration obtained with their optimization and in their works only optimum values of optimization variables are shown. Using these values, in some cases final configurations have not a practical use for their dimensions or cost, which could be very lower giving up little percentage of thermal performance.

The design which performs better in all Index, obviously the second in every p_{ij} only after the p_{ii}, is the one obtained with *TC* minimization. This is easy to understand, because geometric indexes are small thanks to the *IC* minimization which drives towards small exchange areas, and *OC* minimization which acts directly on pumping power. Effectiveness and g, even show good values. In fact, ε and $g_{\Delta T}$ are small because outlet temperatures of fluids are equal in specifications and $g_{\Delta P}$ is reduced by *OC*. However, *TC*-minimization performed adopting a simplified cost correlation has two important problems. Firstly, cost is estimated resorting to the overall surface area only, neglecting manufacturing processes, and geometrical allocation of the area is also neglected, as the same *A* could be obtained with different L, d_o, B, D_s, n and tubes pattern.

Overall, in single-objective optimization economic functions demonstrate their superiority in the optimization of STHE in terms of realizable architecture and general performances. Considering thermal performances could be important in some problems, but an economic quantification of them leads to good results. Anyway, monetary analysis is easy to understand, but the challenge is to formulate OFs which includes all important cost, directly dependent to HE geometric configuration and which could include other performances that could be of interest in different cases.

4.2 Multi-objective optimization results

Using the same case study as above, and considering the OFs declared in Section 3.2, a MOO is performed using the MOGA of Matlab, obtaining a Pareto efficient frontier. In Figure 4 results of *A* - *TC* (a) and *AFP* - *TC* (b) optimizations are depicted. In Figure 5 Pareto front for effectiveness maximization and total cost minimization is instead shown. Decision making tehniques or weighted sum of two OFs allows decision makers to select the preferred trade-off point on the frontier.

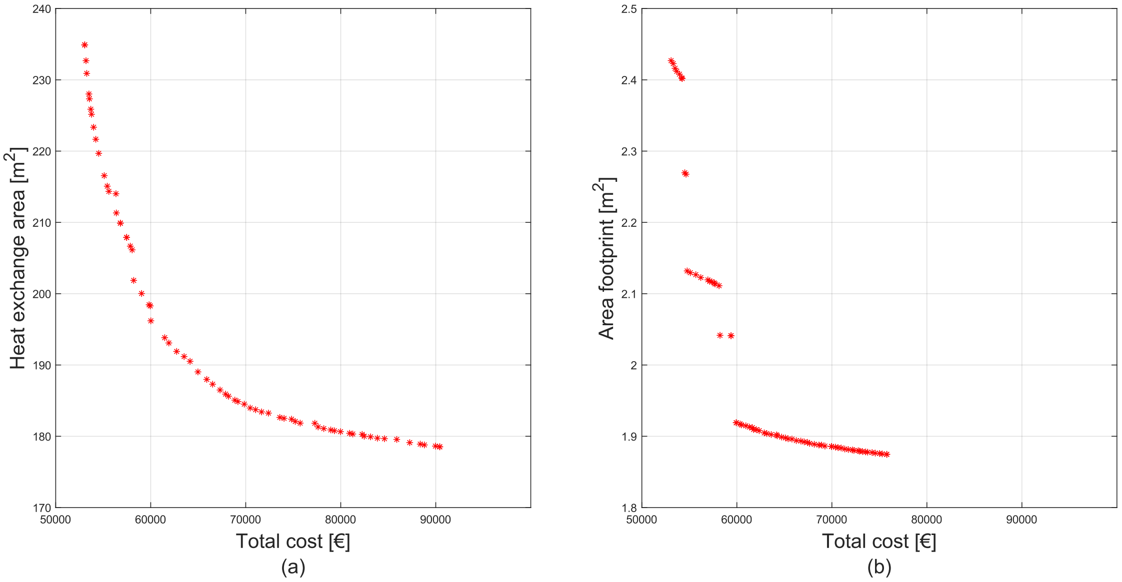

Figure 4 Pareto front of optimized heat transfer area and total cost (a) and optimized area footprint and total cost (b).

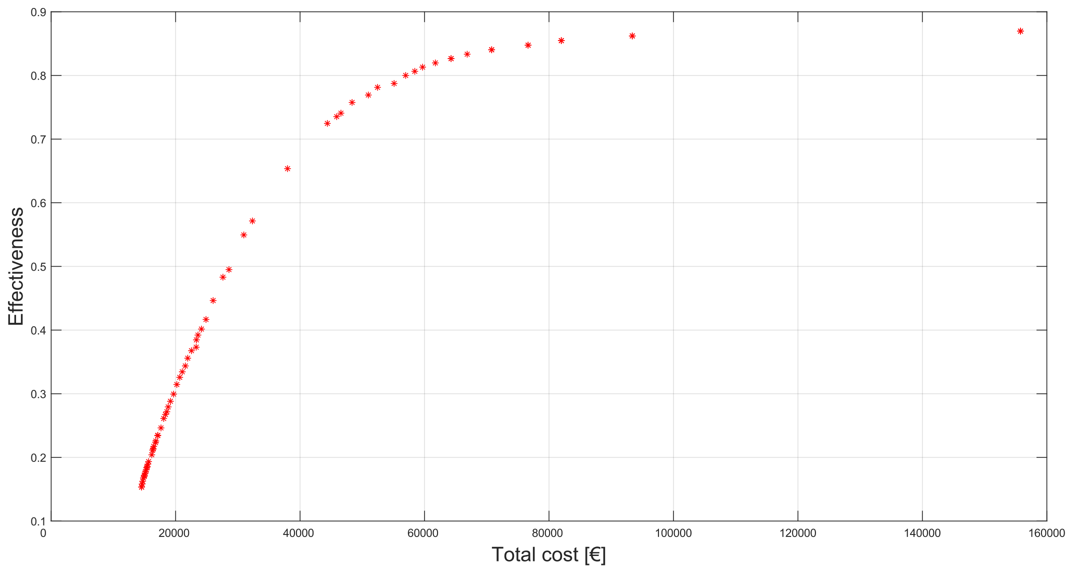

Figure 5 Pareto efficient frontier for effectiveness and TC optimization.

In Figure 4, it can be noticed that when HE area decreases the total cost increases owing to higher fluid velocity and pressure drop. The same occurs in area footprint minimization.

Even if the only interest of designer is HE area minimization, the use of MOGA allows to include TC as well in the configuration decision, so that a good solution is always obtained. In fact, the minimum heat transfer surface found on the frontier is at least one of the least expensive set. Inclusion of TC also allows to obtain good configurations when a thermal performance measure is optimized (Figure 5) without incurring in the unfeasible configuration typical of stand-alone thermal OF optimization.

As noticeable from above results, the same maximum value of effectiveness of single optimization is obtained (ε = 0.87), although *TC* values are quite different. In fact, in the single OF optimization *TC* is 383038 €, whereas in MOO is 155773 €. The TC still remains high in absolute terms (as compared to the about 53000 € of the TC-optimized exchanger), and the equipment configuration remains quite cumbersome, but a significant improvement was obtained compared to sole effectiveness-based optimization. It should also be noted that to further increase effectiveness above the 0.75 threshold is hard to do (in the literature common values of effectiveness are always taken between 0.5 and 0.7) owing to a rapid cost increase determined much higher exchange areas. In this case MOO including total cost proves to be quite useful.

Overall, MOO, apart the difficulty in choosing the preferred point on the Pareto frontier has three main advantages:

- pareto frontier represents the best obtainable solutions space in which designer can move to make decisions;
- given the optimum value of a function, other OF has the better obtainable value: being point of pareto-efficient frontier neither value can be improved without worsening the other one;
- it is possible to minimize/maximize OFs non optimizable with single objective optimization without reaching unfeasible solutions (e.g., thermic performances).

5. IMPLICATIONS FOR DESIGN AND LIMITATIONS OF THE STUDY

Results from this study provide useful guidelines to HE designers, and make a contributions to the advancement of the state of the art in the field of heat exchanger optimal design by shedding some light on a topic neglected by previous literature.

In greater detail the main contributions are the following.

A classification and review of OF has been provided showing that a wide range of alternatives exists, which are seldom justified. The designer is thus left with uncertainty about which kind of OF is to be selected. A clarification in this issue was offered.

It was shown that the choice of the OF is not indifferent, as it heavily impacts on the equipment configuration and the "engineering" quality of the resulting design. Consequences of choosing specific kinds of OF were shown and discussed.

Evidence was provided that geometry-based OFs, aimed at pursuing equipment compactness and/or reduction in capital investment are in general penalized by excessive pressure drop levels and consequent operating costs.

Pressure drop minimizing OF are able to strike a good overall trade-off between thermal, geometrical and economic performances.

OFs based on thermal performances are not advisable, because thermal performance by itself does not define a geometric configuration (i.e. does not help the designer in determining a viable equipment configuration) and from a practical engineering point of view generally delivers scarcely viable solutions, which are affected by excessive costs.

The best solution appears to directly choose a total cost-based OF, as this implicitly dives towards a compromise between area minimization and pressure loss reduction delivering a good overall design which also proves to be cost-effective. In this respect, the designer is advised to include in a cost-based OF definition as much elements as possible amenable to economic quantification (i.e. footprint, maintenance costs, thermal efficiency through economic evaluation of the exchanged energy etc.) as this is an effective manner to include other design objectives having a physical meaning in a balanced design which is also cost-effective. Finally, utilization of economic OFs also simplifies the problem of setting design constraints which, when based on physical parameters, may be difficult to explicit in analytical form manageable by the optimization algorithms. In fact, violation of physical constraints would generally result in equipment configurations with poor cost-effectiveness, which are promptly discarded by using an economic OF. This allows to obtain a good engineering design without explicitly imposing a predefined threshold on the design parameters.

Finally, MOO showed to be useful either to tackle design problems intrinsically multidisciplinary (such as sustainability optimization) and to reduce the risk of scarcely viable design when solely thermal performances are used to drive design optimization.

To the best of our knowledge no previous study explored the role of OF choice in HE optimization, and the obtained results can provide useful guidelines and suggestions for equipment designers.

As far as the limitation of this work are concerned, the main ones can be described as follows.

All results have been obtained referring to a single application example. The analysis should be extended in a wide range of alternative problem instances to confirm validity of the results. Therefore, we do not make any claim of generalization, even if results appear to be generalizable based on engineering reasoning. Only eight objective functions and corresponding performance measures were explored. The analysis could be extended to other performance measures and objectives of interest to the designers. Finally, the analysis is limited to shell and tube heat exchangers, while other equipment configurations could be taken into account. In this respect the use of Kern design procedure does not appear as a limitation, because adoption of other design procedures, such as Bell-Delaware, would have only increased the number of geometrical characteristics observed without affecting the overall results quality.

6. CONCLUSIONS

In this paper, critically reviewing the choice of objective functions in STHE design optimization, it was shown that the choice of the optimization objective is relevant as it can strongly affect the cost-effectiveness and engineering viability of the obtained equipment configuration. Comparison of different objective functions and the resulting equipment configurations under consistent assumptions show that pressure loss minimizing and, above all, total cost minimizing objective functions strike the best trade-off in equipment performances. Caution is mandatory when thermal performances only are being optimized, as this can give rise to unviable and economically unsustainable equipment configurations. Multi-objective optimization assures that the thermal optimum is not dominated from an economic perspective by competing designs. Economic functions are the most used and most interesting from industrial plants point of view. In fact, they are easy to implement and understand. The importance of thermal and geometrical performances is not to be neglected, but the possibility to give an economic value to these aspects is advised.

In future works the formulation of a general purpose objective function that includes from an economic point of view thermo-fluid-dynamic, geometrical, and economical performances will be examined in greater detail and the possibility of extending the analysis from deterministic to stochastic design problems will be also explored.

NOMENCLATURE

Symbol	Unit	Caption	Symbol	Unit	Caption
A	[m^2]	Heat transfer area	*L*	[m]	Tube length
a_1	[-]	Numerical constant	*m*	[kg/s]	Mass flow rate
a_2	[-]	Numerical constant	*n*	[-]	Number of tube passages
a_3	[-]	Numerical constant	*Nt*	[-]	Tubes number
AFP	[m^2]	Footprint in plant	*Ny*	[y]	Equipment life
B	[m]	Baffle spacing	*NTU*	[-]	Number of thermal units
C^*	[-]	Ratio of capacity rates	*OC*	[€/y]	Operating cost
Cen	[€/kWh]	Energy cost	*P*	[kW]	Pumping power
Cl	[m]	Clearance	*Pattern*	[-]	Tubes pattern
c_p	[kJ/kgK]	Specific heat	*Pr*	[-]	Prandlt number
De	[m]	Equivalent diameter	*Pt*	[m]	Tube pitch
do	[m]	Tube outer diameter	*Q*	[W]	Duty
DOC	[€]	Discounted operating cost	*Re*	[-]	Reynolds number
D_s	[m]	Shell diameter	*Rf*	[m^2 K/W]	Conductive fouling resistance
F	[-]	Temperature difference corrective factor	*S*	[m^2]	Heat exchanger surface
g	[-]	Number of entransy dissipation units	*TC*	[€]	Total cost
H	[h/yr]	Annual operating time	*t*	[°C]	Fluid temperature
h	[W/m2K]	Heat transfer coefficient	*Tube Side*	[-]	Fluid tube side passage
i	[%/y]	Annual discount rate	*U*	[W/m^{2}K]	Global heat transfer coefficient
IC	[€]	Investment cost	*VFP*	[m^3]	Volumetric footprint
L/D	[-]	Length diameter ratio	*v*	[m/s]	Fluid velocity
LMTD	[°C]	Logarithmic mean temperature difference			

SUBSCTIPTS			GREEK SYMBOLS		
Symbol	**Unit**	**Caption**	**Symbol**	**Unit**	**Caption**
c	[-]	Cold fluid	ΔP	[Pa]	Pressure drop
h	[-]	Hot fluid	ε	[-]	Effectiveness
i	[-]	Inlet	η	[-]	Overall pumping efficiency
o	[-]	Outlet	λ	[W/mK]	Thermal conductivity
s	[-]	Shell side	μ	[Pa s]	Viscosity
t	[-]	Tube side	ρ	[kg/m^3]	Density

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