DOI: 10.2507/36th.daaam.proceedings.015

DESIGN-ORIENTED SOBOL' SENSITIVITY ANALYSIS OF KEY PARAMETERS IN PLATE HEAT EXCHANGER OPTIMISATION

Zaid Al-Dailami, Anas F. A. Elbarghthi, Vaclav Dvorak & Jaroslav Hlava

This Publication has to be referred as: Al-Dailami, Z[aid]; Elbarghthi, A[nas] [F.] [A.]; Dvorak, V[aclav] & Hlava, J[aroslav] (2025). Design-Oriented Sobol' Sensitivity Analysis of Key Parameters in Plate Heat Exchanger Optimisation, Proceedings of the 36th DAAAM International Symposium, pp.0116-0121, B. Katalinic (Ed.), Published by DAAAM International, ISBN 978-3-902734-47-1, ISSN 1726-9679, Vienna, Austria
DOI: 10.2507/36th.daaam.proceedings.015

Abstract

Plate heat exchangers (PHEs) are widely used across industries due to their compactness, high efficiency, and reliability. However, their performance can be substantially improved through targeted design optimisation. This study focuses on optimising a one-dimensional PHE model, validated through both experimental data and CFD simulations. The goal is to enhance thermal effectiveness while minimising pressure drop by adjusting key geometric parameters within feasible limits. A multi-objective optimisation strategy is employed to balance these competing performance goals. To reduce computational effort and improve efficiency, a pre-optimisation sensitivity analysis using Sobol's method identifies the most influential variables. This allows the design space to be reduced from six parameters to two without compromising accuracy. The channel gap is found to be the dominant factor affecting pressure drop, contributing over 50% to its variation. In contrast, plate thickness has the greatest impact on thermal effectiveness, accounting for more than 40% of the total and interaction effects. These insights enable more targeted design adjustments and demonstrate the value of integrating sensitivity analysis into the optimisation process. Overall, the study presents an effective and computationally efficient approach to improving PHE performance in industrial applications.

Keywords: Plate Heat Exchanger; multi-objective optimisation; Pareto front; Sobol's sensitivity analysis.

1. Introduction

PHEs have emerged as essential components in a broad range of industrial applications, including power generation, chemical processing, food manufacturing, and HVAC systems, owing to their compactness, ease of maintenance, and exceptional heat transfer efficiency [1]. Their unique design, which incorporates thin, corrugated plates to promote turbulence, results in heat transfer coefficients that far exceed those of conventional shell-and-tube exchangers [2]. This has led to widespread adoption of PHEs, driving ongoing research to further enhance their performance and reliability. The European market for PHEs, valued at $1.7 billion in 2023 and projected to reach $3.3 billion by 2032, reflects the strong demand for efficient and reliable heat exchanger solutions. Notably, over a quarter of this market (around 27.2%) cater to central heating and refrigeration applications, highlighting the increasing importance of optimisation and sensitivity analyses in PHE design [3].

In recent years, sensitivity analysis has become a valuable tool for measuring how variations in design parameters such as plate geometry, fluid properties, and fouling influence PHE performance [4]. These analyses give engineers essential insights to prioritise design changes and optimise operating conditions, thereby boosting energy efficiency and operational resilience [5]. This approach is especially important as industries face increasing demands for sustainable and cost-effective thermal management solutions [6].

Advancements in sensitivity analysis have integrated Monte Carlo simulations with global sensitivity indices, such as Sobol' indices, to quantify parameter influence effectively. To reduce computational cost, surrogate models like Polynomial Chaos Expansions and Gaussian Processes have been employed, enabling analytical or efficient estimation of sensitivity metrics [7],[8]. Additionally, machine learning–based surrogates have further enhanced sensitivity analysis by capturing complex parameter interactions and uncertainties [9]. Moreover, sensitivity analysis is often combined with multi-objective optimisation frameworks to identify critical variables and fine-tune exchanger designs for specific industrial requirements [10].

In this context, the current study demonstrates that merging sensitivity analysis with optimisation strategies, by maximising heat transfer efficiency while minimising pressure drop, leads to PHE designs with superior performance and reduced energy consumption. Specifically, the research applies a Sobol' sensitivity analysis and a pre-processing approach to identify the most influential parameters, thereby streamlining the multi-objective optimisation process and achieving faster and more efficient results.

2. Heat Exchanger Optimisation

The plate to be optimised is already available on the market and used in many refrigeration applications [11]. Figure **1** illustrates the geometrical specifications of the investigated plate, and its dimensions can be seen in Table **1**.

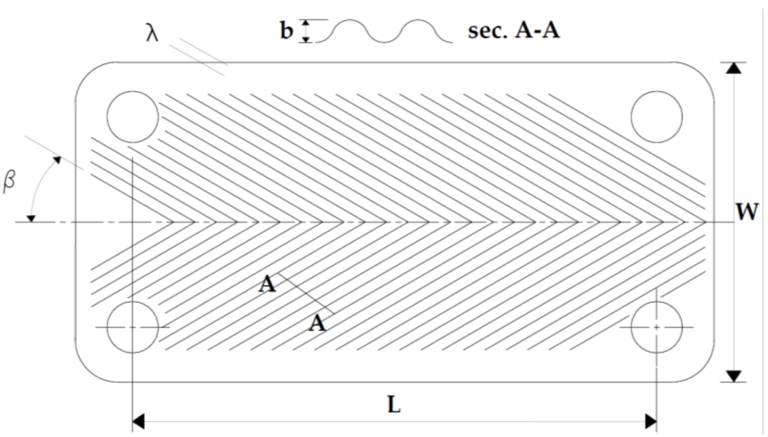

Fig. 1. Schematic illustration of the investigated PHE

Geometry parameter	Value
Effective flow length, L (mm)	250
Plate thickness, t_{pl} (mm)	0.6
Port diameter, D_{po} (mm)	30
Plate pitch, P_i (mm)	2.5
Mean channel gap, b (mm)	1.9
Plate width, W (mm)	95
Corrugation pitch, λ (mm)	6.8
Corrugation angle, β (°)	64

Table 1. Geometric characteristics of the investigated PHE.

2.1 Multi-objective optimisation Process

The main objective of this research is to identify an optimised shape that provides high thermal performance. Specifically, the aim is to maximise effectiveness ε, while reducing pressure drop ΔP across both channels of the plate heat exchanger (hot and cold). This is achieved by adjusting the geometrical parameters of the plate. Formally, the optimisation problem is defined as:

$$\max_{x \in D} \varepsilon(x) \quad , \quad \min_{x \in D} \Delta P(x) \tag{1}$$

subject to the constraints:

$$g_j(x) \leq 0, \quad j = 1, \ldots, J \tag{2}$$

$$x_{lower} \leq x \leq x_{upper} \tag{3}$$

where x is the design vector of parameters in Table 2: $x = (\beta, b, \lambda, t_{pl}, D_{po}, N_{pt})$, D is the feasible design space constrained by the constraint function $g_j(x)$, x_{lower} and x_{upper} represent the lower and upper bounds of the parameters. The outcome of this multi-objective optimisation is the Pareto front, which represents the trade-off and optimal balance between the conflicting objectives. The overall optimisation procedure consists of Kriging metamodeling in the adaptive sampling step and a multi-objective genetic algorithm (NSGA-II) [12]. The NSGA-II algorithm, implemented via MATLAB's built-in gamultiobj function, is employed as the optimisation engine. It follows key steps: evaluating the objective functions for a parameter vector, selecting the best individuals based on the Pareto relationship, recombining genes to create new solutions, and applying mutations to explore additional possibilities.

2.2 Sobol' Sensitivity analysis

To identify the most influential design parameters in PHEs, Sobol' sensitivity analysis is used. This variance-based global sensitivity analysis method breaks down the output variance into contributions from individual input variables and their interactions. If the six design parameters characterised in Table **2** are within the specified optimisation range, then the performance metric of interest, such as effectiveness (ε) and pressure drop (ΔP), is denoted as cap Y. The total variance of cap Y is decomposed as[13]:

$$Var\,(Y) = \sum_{i=1}^{6} V_i + \sum_{i<j} V_{ij} + \cdots + V_{1,2,\ldots,6} \tag{4}$$

where V_i is the variance contribution from parameter i alone, and V_{ij} is the contribution from the interaction between parameters i and j, and so on. The first-order Sobol' index for parameter i is:

$$S_i = \frac{V_i}{Var(Y)} \tag{5}$$

This index quantifies the effect of varying parameter i alone on the output variance. The total-effect index, accounting for all interactions involving parameter i, is:

$$S_{T_i} = 1 - \frac{Var_{\sim i}(E[Y|X_{\sim i}])}{Var(Y)} \tag{6}$$

where $X_{\sim i}$ denotes all parameters except i. Applying this methodology to PHE design allows for the identification of parameters that significantly influence performance metrics.

Design Parameters	**Lower Limit**	**Higher Limit**
Number of plates N_{pt}	50	110
Plate thickness, t_{pl} (mm)	0.2	1
Port Diameter, D_{po} (mm)	20	40
Mean channel gap, b (mm)	0.9	2.9
Corrugation pitch, λ (mm)	3.8	10
Corrugation angle, β (°)	30	70

Table 2. Upper and lower limits of design parameters.

3. Results and discussion

This section presents the optimisation results both before and after incorporating the Sobol' sensitivity analysis. It demonstrates how this analysis enhances understanding of variable tendencies and their impact on system performance. By identifying and focusing on the most influential parameters, the analysis enables a reduction in the number of design variables. This leads to faster computations, reduced computational costs, and more precise optimisation results.

3.1. Sobol' sensitivity analysis

The optimisation aims to achieve two objectives: minimising the pressure drop for the two channels, hot and cold, and maximising the effectiveness. Consequently, a multi-objective optimisation approach is required. However, such an approach can be computationally expensive, particularly when multiple design variables are involved.

To address this, a preliminary advanced analysis is performed to better understand the behaviour of the design variables with respect to the objective functions. Figure **2** presents the Sobol' sensitivity analysis results for the six considered variables. The channel gap emerged as the most influential parameter for pressure drop, with first-order Sobol' indices near 52% and contributing around 70% when interactions are considered. While the corrugation angle had a minimal direct effect on effectiveness (total effect of 26.3%), it significantly influenced flow and turbulence patterns. Plate thickness was a key factor affecting effectiveness, accounting for 43% of the variance individually. Plate thickness and mean channel gap have a similar effect on effectiveness. Lastly, the corrugation pitch had a negligible impact on pressure drop but contributed 13.51% to effectiveness.

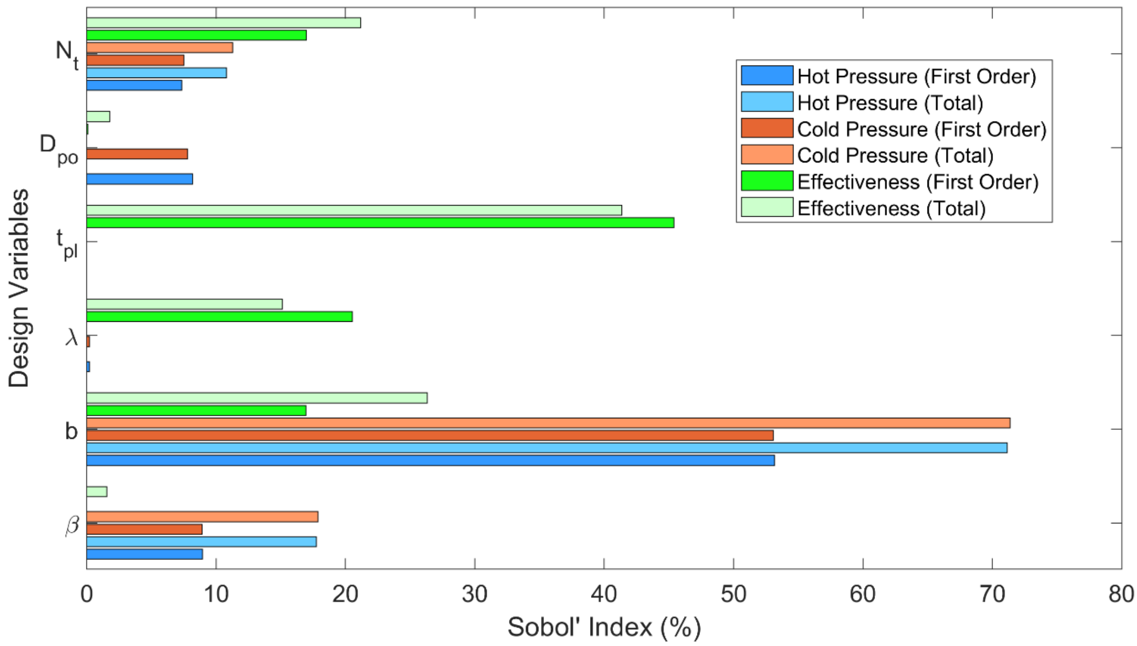

Fig. 2. Sobol' sensitivity analysis on the three objective functions for six design variables.

Figure **3** illustrates how the design variables are distributed in the best solutions along the Pareto front. From the figures, it is evident that some variables remain unchanged throughout the analysis, specifically, $\beta, \lambda, t_{pl}, N_{pt}$. As these parameters show little to no variation, they can be fixed as constants in the optimisation process. Consequently, optimisation can be focused on the two variables that exhibit variation: b and D_{po}.

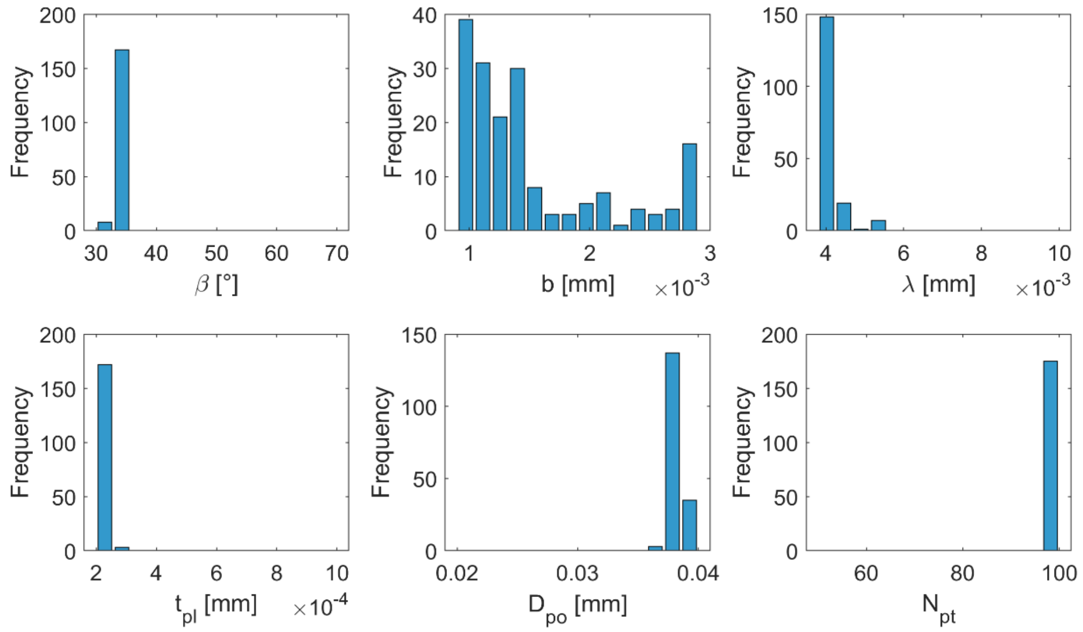

Fig. 3. Distribution of Design Variable Values in Pareto-Optimal Solutions

3.2. Results before and after the pre-analysis

The results of the six-variable optimisation and the improved two-variable optimisation are shown in Figure **4**. The results clearly indicate that concentrating on the two most adjustable variables, b and D_{po}, yields more accurate and efficient outcomes, even with fewer samples of the population and generations.

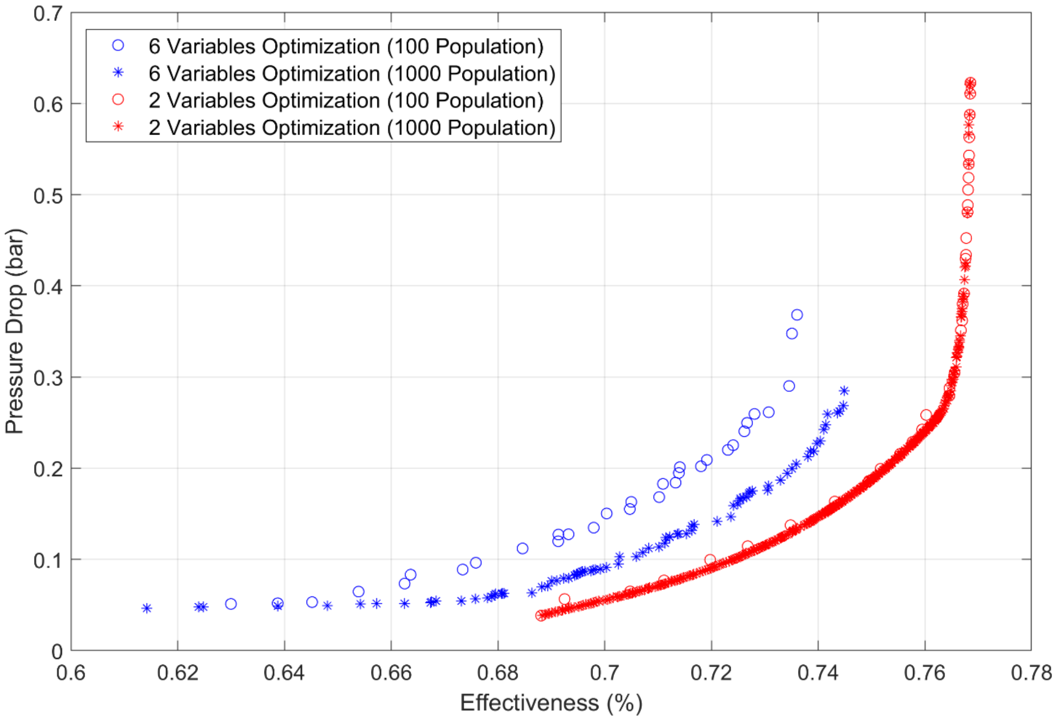

Fig. 4. Impact of Variable Reduction on Optimisation Performance.

Figure **4** shows the Pareto plots for the optimisation results. The blue plots represent optimisation with 6 design variables, while the red plots correspond to optimisation with 2 design variables. The blue circular points indicate the Pareto front obtained using six design variables, a population of 100 individuals, and 20 generations. The star points denote results with a larger population of 1000 samples, illustrating that a higher population size improves accuracy and efficiency in pressure drops and effectiveness. Conversely, the red points display the results after reducing the variables from six to two. Notably, even with fewer variables or generations, the two-variable optimisation achieves more robust and efficient outcomes. These results exemplify the core principle of simulation, which is experimenting with the purpose of better understanding and improving the system [**14**]. In terms of computational costs, simulations with a population of 100 samples took approximately one minute, while simulations with 1000 samples took around 10 minutes.

While the proposed optimisation approach combining Sobol' sensitivity analysis with multi-objective optimisation has demonstrated significant improvements in computational efficiency and accuracy, the study is subject to several limitations that should be acknowledged. First, the optimisation process was conducted within a limited operating temperature range of 20°C to 60°C, which may not reflect performance under more extreme or industrial conditions. Second, the analysis was restricted to six design variables, each constrained within specific ranges as defined in Table 2. This may limit the generalisability of the results to other heat exchanger configurations with different or additional design parameters. Furthermore, the simulation exclusively considered water as the cooling medium, meaning the influence of alternative fluids with varying thermal properties remains unexplored. In addition, the optimisation was performed using a maximum population size of 1000 and 20 generations, which, while sufficient for this case, may not capture the full solution space in more complex models or systems requiring higher-resolution optimisation. These constraints define the scope of the present study and provide direction for future research aimed at extending the applicability and robustness of the proposed method.

4. Conclusion

This study addresses a key challenge in the optimisation of plate PHEs. The challenge is the excessive computational time required when handling multiple design variables in multi-objective optimisation. To overcome this issue, a combined approach was developed that integrates Sobol' sensitivity analysis with multi-objective optimisation. This method enables the identification of the most influential variables for each objective function, significantly reducing the dimensionality of the optimisation problem.

The sensitivity analysis revealed that the channel gap is the dominant factor affecting pressure drop, accounting for more than half of the total variability, while plate thickness is the most influential variable for heat exchanger efficiency, contributing 42.6% to the combined direct and interaction effects. By isolating the parameters that have the greatest impact, the original six-variable optimisation problem was reduced to just two key variables. This reduction led to a more focused and computationally efficient optimisation process. As a result, the refined model generates accurate and high-quality Pareto fronts in a matter of minutes instead of hours without even better performance as shown in figure 4. This confirms that integrating sensitivity analysis into the optimisation workflow enhances both speed and accuracy.

Future work will explore applying this combined optimisation method to other PHE designs currently available on the market to further assess its generalisability and effectiveness. Additionally, the approach will be extended to examine the impact of alternative cooling fluids beyond water, enabling a broader evaluation of thermal performance across various operating conditions.

5. Acknowledgements

This work was supported by the Student Grant Competition of the Technical University of Liberec under project No. SGS-2023-5323

6. References

[1] Kumar, S., Singh, S. K., & Sharma, D. (2022). A comprehensive review on thermal performance enhancement of plate heat exchanger. Inter. Journal of Thermophysics, 43(7), 109.

[2] Ham, J., Lee, G., Kwon, O., Bae, K., & Cho, H. (2023). Numerical study on the flow maldistribution characteristics of a PHEs. Applied Thermal Engineering, 224, 120136.

[3] Gupta, A., & Sharma, D. (2024). Europe plate heat exchanger market – By application (oil and gas, chemical, power generation and metallurgy, marine, mechanical industry, central heating and refrigeration, food processing) and forecast, 2024–2032. Retrieved from

[4] Valencia, G., Núñez, J., & Duarte, J. (2019). Multiobjective optimisation of a plate heat exchanger in a waste heat recovery organic rankine cycle system. Entropy, 21(7), 655.

[5] Wang, Y., Yu, M., Fan, H., & Chung, J. D. (2025). Multi-Objective Topology Optimisation of Cold Plates for Enhanced Battery Thermal Management in Electric Vehicles. Case Studies in Thermal Engineering, 105794.

[6] Zhang, J., Wang, Q., Shu, C. M., Zhang, M., & Lin, J. (2021). A multi-objective optimisation method for under-the-hood thermal management of vehicles. Applied Thermal Engineering, 192, 116818.

[7] Sudret, B. (2008). Global sensitivity analysis using polynomial chaos expansions. Reliability engineering & system safety, 93(7), 964-979.

[8] Le Gratiet, L., Marelli, S., & Sudret, B. (2017). Metamodel-based sensitivity analysis: polynomial chaos expansions and Gaussian processes. In Handbook of uncertainty quantification (pp. 1289-1325). Springer, Cham.

[9] Darges, J. E., Alexanderian, A., & Gremaud, P. A. (2024). Extreme learning machines for variance-based global sensitivity analysis. International Journal for Uncertainty Quantification, 14(4).

[10] Meng, L., Liu, J., Bi, J., Özdemir, E. D., & Aksel, M. H. (2023). Multi-objective optimization of plate heat exchanger for commercial electric vehicle based on genetic algorithm. Case Studies in Thermal Engineering, 41, 102629.

[11] Tenez a.s., Welded heat exchanger accessed: 2025-02-03.

[12] Mastrippolito, F., Aubert, S., Ducros, F., Ferrand, M., & Fourmigué, J. F. (2018, June). Multi-objective shape optimisation of a plate heat exchanger: a multi-scale approach. In International Conference on Energy Engineering and Smart Grids.

[13] Le Guyadec, M., Gerbaud, L., Vinot, E., & Delinchant, B. (2019). Sensitivity analysis using Sobol indices for the thermal modelling of an electrical machine for sizing by optimization. COMPEL-The international journal for computation and mathematics in electrical and electronic engineering, 38(3), 965-976.

[14] Rakic, K. (2021). Application of agent-based modelling and simulation tools. DAAAM International Scientific Book. ISBN 978-3-902734-31-0, ISSN 1726-9687, Vienna, Austria