ENHANCED INHERENT SAFETY ASSESSMENT DURING HEAT EXCHANGER NETWORK SYNTHESIS

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Abstract This study aims to accurately assess the inherent safety of a heat exchanger network during synthesis in the early stage of design. It is a challenging task, as for accurate estimation of mass present in the heat exchangers, detailed design is required. An iterative procedure was used, synthesizing the heat exchanger network (HEN) first, followed by a detailed design of each heat exchanger separately and, finally, updating the heat exchanger network synthesis model based on the designs of the heat exchangers. For both the synthesis and the heat exchanger design, mixed-integer nonlinear programming (MINLP) models were used. The results show the impact of accurate sizing of exchangers for individual heat transfers, as the results varied by up to 73 % in risk assessment, while the net present value of the HEN before and after detailed heat exchanger design remained essentially the same.

Keywords:
mathematical modeling,
heat exchanger network,
inherent safety,
process optimization,
process synthesis.

University of Maribor Press

DOI https://doi.org/10.18690/978-961-286-353-1.20
ISBN 978-961-286-353-1

1 Introduction

The Circular Economy provides great benefits for society as well as for the environment, but only when planned carefully. The processes in a Circular Economy are closely connected to each other; hence, much depends on each one, so it is crucial that each process operates properly. Also, the consequences reach far beyond the limits of each process. One of the most important aspects of operability is the safety of the processes. Process safety must be considered during the planning, installation, and operation of plants. Special attention should be paid to inherent safety, presenting all the potential hazards in each process resulting from substances used, process conditions, equipment, and process design. As the major decisions that heavily influence the inherent safety of a plant are made during the early stages of planning, inherent safety must be taken into account in those stages (Kletz, 1996).

There has been a great deal of work done on developing and testing inherent safety indexes; however, only a few studies have been done in the area of process synthesis considering inherent safety.

In this study, the aim is to enhance the assessment of inherent safety (risk) indexes during Heat Exchanger Network synthesis by considering the exact geometry of each Heat Exchanger type.

2 Methodology

A three-stage approach was used to synthesize a HEN using enhanced safety assessment. A superstructure approach based on mathematical programming was used to synthesize the HEN.

In Step 1, the initial HEN model synthesis was performed, as described in Nemet *et al.* (2017), using estimated area density factors for volume, mass and, consequently, for risk indicator assessment. After obtaining an initial HEN, each heat exchanger was optimized separately, based on the selected type of heat exchanger.

In Step 2, models for determining the optimal geometry of each heat exchanger were developed using descriptions from Goričanec *et al.* (2008), Goričanec (2015), Goričanec and Trop (2016). In this work, only shell type, tube type and plate type heat exchangers were considered. The models for heat exchangers took into account: i) the proper Ft correction factor for heat exchanger logarithm mean temperature, ii) appropriate velocity and pressure drop within pipes and on the shell side, iii) type of flow (laminar, turbulent, transitional) and iv) number of passes. For shell and tube heat exchangers, we also took into account the: i) inner and outer radius of the pipe, ii) the pipe arrangement (triangle and quadratic), iii) standardized number of pipes.

In the last Step 3, the updated correction factors, volume-to-area ratio, and heat transfer coefficient were used to obtain the final HEN.

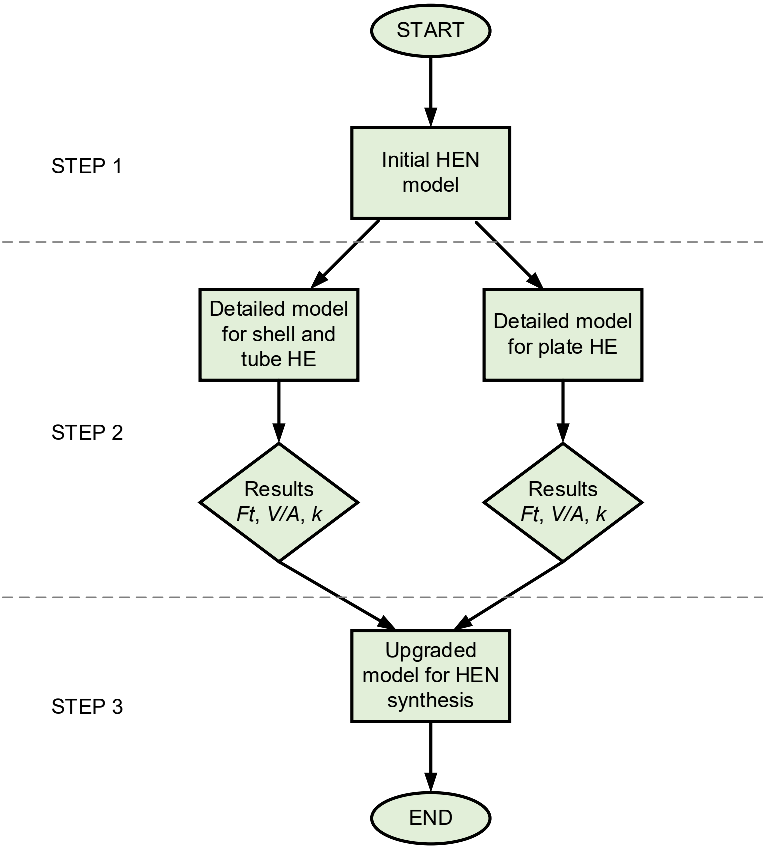

Figure 1: Work flowsheet presenting the three-step approach.

2 Case study

The procedure was tested on an illustrative case study. The input data is presented in Table 1. As can be seen, all the main properties of the substances are required to enable the detailed geometry optimization of heat exchangers as well as the risk assessment.

Table 1: Input data for entire HEN synthesis.

	Hot streams		**Cold streams**	
Property	**H1**	**H2**	**C1**	**C2**
Supply temperature / K	490	550	330	390
Target temperature /K	400	510	400	440
Heat capacity flowrate / kW K^{-1}	44	27	20	30
Heat transfer coefficient / W $m^{-1}K^{-1}$	0.144	0.244	0.144	5.944
Boiling temperature at 1 bar /K	338	112	82	20
LC 50 /mg m^{-3}	26,000	13,000	5,348	1,227
State	gas	gas	gas	gas
Flammable	yes	yes	yes	yes
Energy, released at explosion/ kJ kg^{-1}	4 670	142	10	2 253
Density / kg m^{-3}	45	18.6	49	16
Dynamic viscosity / kPa s	0.0151	0.01761	0.0167	0.0153
Specific heat / J kg^{-1} K^{-1}	5 270	3 000	1 045	14 490
Conductivity / W m^{-1} K^{-1}	0.0741	0.0741	0.0240	0.239
Thermal resistance / K m^2 W^{-1}	0.00036	0.00036	0.00036	0.00036

2.1 Initial HEN synthesis - Step 1

Figure 2 presents the HEN obtained using the initial HEN synthesis. The HEN consists of one shell and tube exchanger and two plate heat exchangers.

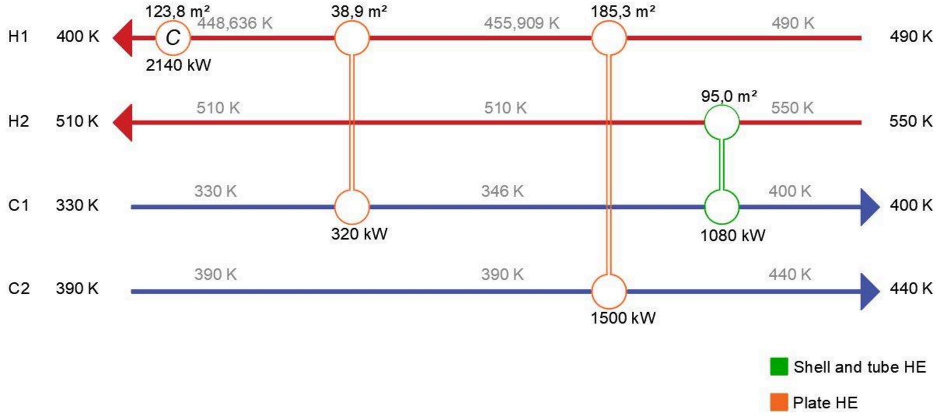

Figure 2: HEN obtained in step 1.

2.2 Optimization of each heat exchanger- Step 2

Figure 3 presents the masses of substances present in the heat exchanger in relationship to its geometry. Figure 3a presents the shell and tube heat exchanger with a triangular distribution of tubes having an inner diameter of 19.05 mm, while Figure 3b presents the results with a triangular distribution of tubes and an inner tube diameter of 25.4 mm. Figure 3c presents the result of a quadratic distribution of tubes with an inner diameter of 19.05 mm.

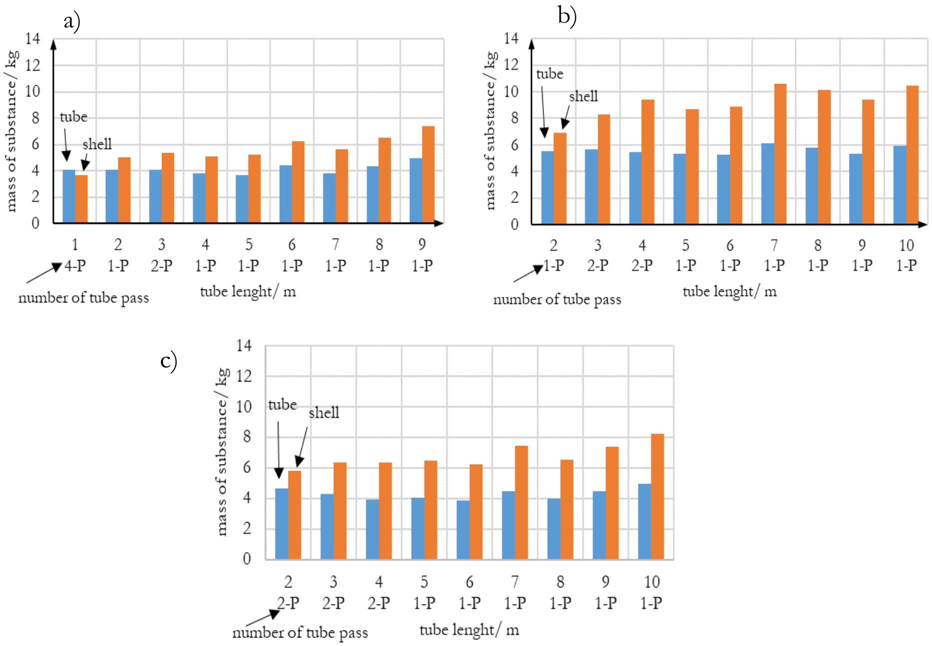

Figure 3: Mass present in the heat exchanger at different geometries, when triangular tube distribution with a) 19.05 mm tube inner diameter, b) 25.4 mm tube inner diameter and c) quadratic tube distribution with 19.05 mm tube inner diameter in various tube lengths.

The smallest mass was present in a heat exchanger with 5 m tube length, in a triangular arrangement where the inner diameter of the tubes was 19.05 mm. Therefore, this solution was taken as the optimal geometry.

For plate heat exchangers, a sensitivity analysis was performed considering the width and the height of the plates for heat exchange between streams H1-C1 and H1-C2. The mass of the heat exchanger in the first exchange is presented in Figure 4a, while the second is presented in Figure 4b.

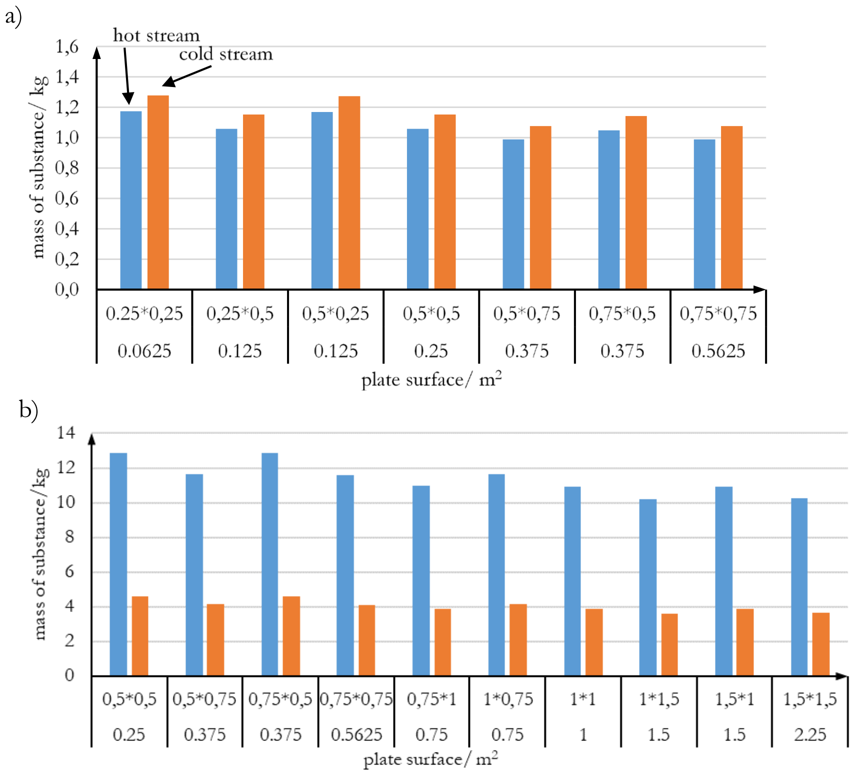

Figure 4: Mass of material in a plate heat exchanger between streams a) H1-C1 and b) H1-C2.

In Figure 4a, the smallest mass present in the heat exchanger between H1-C1 is in the one with a plate dimension of 0.5 ×0.75 m, while from Figure 4b the smallest mass present in the heat exchanger is in one with plate dimensions of 1×1.5 m.

2.3 Updated HEN synthesis- Step 3

The overall HEN synthesis was performed again after obtaining the optimal design of each heat exchanger. The updated data is presented in Table 2.

Table 3 provides a comparison between a HEN obtained by initial synthesis and synthesis with the updated model.

Table 1: Comparison of the data used in the initial and the updated model.

	Initial model	**Updated model**
Logarithm mean temperature correction factor		
Shell and tube (H2-C1)	0.8	0.958
Plate (H1-C1)	1	1
Plate (H1-C2)	1	0.988
Ratio between volume and area / $m^3\ m^{-2}$		
Shell and tube (H2-C1)	0.055	tube: 0.00326 shell: 0.00196
Plate (H1-C1)	0.00143	0.001726
Plate (H1-C2)	0.00143	0.001756
Heat transfer coefficient / $W\ m^{-1}K^{-1}$		
Shell and tube (H2-C1)	H2: 0.244, C1: 0.144	0.1198
Plate (H1-C1)	H1: 0.144, C1: 0.144	0.2203
Plate (H1-C2)	H1: 0.144, C2: 5.944	0.2046

Table 3: Comparison of selected results between designs obtained with the initial and the updated model.

	Initial model	**Updated model**	**Difference**	**Difference /%**
Area /m^2				
Shell and tube (H2-C1)	38.91	12.72	26.19	67.3
Plate (H1-C1)	185.26	128.86	56.41	30.4
Plate (H1-C2)	95.02	59.99	35.03	36.9
Toxicity				
Shell and tube (H2-C1)	1.6987×10^{-6}	6.7065×10^{-7}	1.0280×10^{-6}	60.5
Plate (H1-C1)	1.8100×10^{-5}	1.5475×10^{-5}	2.6251×10^{-6}	14.5
Plate (H1-C2)	1.1277×10^{-5}	3.0168×10^{-6}	8.2602×10^{-6}	73.2
Flammability				
Shell and tube (H2-C1)	5.0962×10^{-7}	2.0120×10^{-7}	3.0842×10^{-7}	60.5

Plate (H1-C1)	1.6158×10^{-6}	1.3814×10^{-6}	2.3439×10^{-7}	14.5
Plate (H1-C2)	3.3831×10^{-6}	9.0503×10^{-7}	2.4781×10^{-6}	73.2
Explosiveness				
Shell and tube (H2-C1)	2.5473×10^{-9}	1.0057×10^{-9}	1.5416×10^{-9}	60.5
Plate (H1-C1)	1.4177×10^{-8}	1.2121×10^{-8}	2.0565×10^{-9}	14.5
Plate (H1-C2)	3.5050×10^{-10}	1.2330×10^{-10}	2.2721×10^{-10}	64.8
Net present value/ k€	4131.643	4132.372	0.729	0.0138

3 Conclusions

We have developed a method using a three-step approach for detailed heat exchanger design and, consequently, a more accurate risk assessment during HEN synthesis. In each step, a MINLP model was used. As the results indicate, for a basic trade-off between operating cost and investment using Net Present Value (NPV) as a criterion, the initial model for HEN synthesis provides acceptable results, as the difference between the initial and the updated HEN models in NPV is negligible. However, when a comparison of the risk assessment is performed, the differences are larger: up to 73 % difference was obtained in the risk assessment indicator. This leads to the conclusion that for accurate risk assessment, detailed heat exchanger geometry must be considered.

Acknowledgments

The authors acknowledge financial support from the Slovenian Research Agency, program P2-0032 and project J7-1816.

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