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# A METHODOLOGY TO ESTIMATE PIPE LENGTH IN HEAT EXCHANGER NETWORKS AT THE DESIGN STAGE

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***Abstract:*** *Heat exchanger networks (HEN) are widely used in industrial processes to reduce energy consumption. HEN synthesis procedures both for initial screening of possible options and for designing the network structure are well known, available in the open literature and in commercial software. Most commonly, utility and heat exchanger costs are the main consideration for HEN design. However, at the process implementation stage, piping and pumping material is needed to transport streams through the equipment as well as the heat exchangers. Piping and pumping costs may influence the HEN topology depending on how equipment is arranged in the process plant layout. Thus, the match-selection stage should be carried out taking these costs into account. This paper presents an improved methodology to estimate the pipe length required for the process streams to exchange heat, which can then be used to estimate piping and pumping costs. In an industrial site, process streams run through one piece of equipment to another, such as tanks, reactors, separators, etc. The heat exchangers of the HEN are located between these pieces of equipment for the streams to achieve their thermal requirements. Existing methods for piping length estimate use the physical coordinates of the equipment that is located at the starting point of the process streams, leading to a rather conservative pipe-length value. We show that by including both the starting point and the endpoint of the process streams, a better estimate can be obtained. These methods only require knowledge of the equipment location and are thus very simple to implement. We then proceed to improve the methodology by considering the entire routes of the process streams and the deviations to reach the desired heat exchanger. This approach, called Shortest Length Method (SLM), results in a linear programming model, albeit slightly more complex to solve than the previous methods, it presents a much better estimate of the actual pipe length required for the network. A case study was used to test the methodologies. For a process with seven process streams and six integrated exchangers, the estimated pipe lengths were 470, 286, and 228 length units for the methods: traditional, improved and SLM, respectively. The proposed methodology enables the attribution of a pipe length value to each potential match prior to the HEN synthesis as well as the estimation of pipe length incurred from the heat exchanges in an already designed HEN.*
***keywords:*** *plant layout, heat exchanger network, pipe length, piping*

## 1. INTRODUCTION

The energy consumption of industrial processes can be reduced by maximising the heat exchanges between the process streams with HENs. The synthesis of HEN is usually accomplished considering the utility and heat exchanger investment costs (Smith, 2005; Kemp and Shiun Lim, 2020). Recent research has included the lengths of the pipelines to estimate the piping and pumping costs for the transport of the streams through the plant layout (Pouransari and Maréchal, 2014; Souza *et al.*, 2016; Rathjens and Fieg, 2018). The lengths of the pipelines are related to the locations of the heat exchangers and the connected equipment. The heat exchangers should be located near the connected equipment with due consideration to process, safety, cleaning and maintenance requirements (Bausbacher and Hunt, 1993; Moran, 2016; Barker, 2018).

Consider a process with hot stream $i$ and cold stream $j$. For simplification, the process layout is restricted to two dimensions. In this process, hot stream $i$ runs from a storage tank to a reactor, and cold stream $j$ runs from a separator to a distillation column, as depicted in Fig. (1). The distance run by streams $i$ and $j$ between the equipment is 4 length units each. Consider now that a heat exchanger is installed in the process, with heat being exchanged between both streams. As a consequence streams $i$ and $j$ run through different routes in the process plant. Stream $i$ runs from the storage tank to the heat exchanger, and from the heat exchanger to the reactor. Stream $j$, in its turn, runs from the separator to the heat exchanger and from the heat exchanger to the distillation column, as shown in Fig. (2).

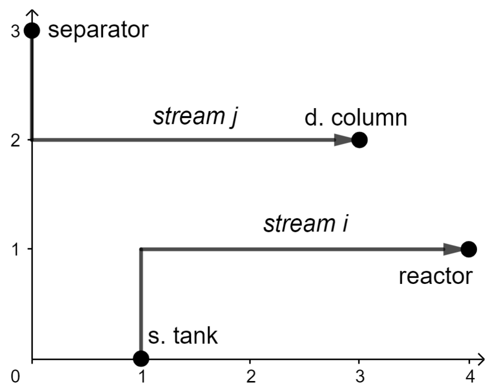

Figure 1: Routes of streams $i$ and $j$.

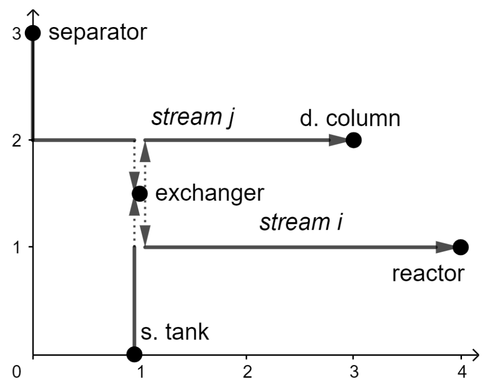

Figure 2: Routes of streams $i$ and $j$ with the heat exchanger.

With the new layout due to the positioning of the heat exchanger, the distance run by each stream increases from 4 to 5 length units. Thus, the heat exchanger represents a net increase of 1 length unit in distance run by streams $i$ and $j$. This net increase can also be understood as the additional distance run by streams $i$ and $j$. The term "additional" is used in the sense that streams $i$ and $j$ would not have to run such distance if the heat exchanger did not exist. The additional distance must not be confused with the distance run by streams $i$ and $j$ from their starting points to their endpoints. With or without the heat exchanger, streams $i$ and $j$ have to run from their starting points to their endpoints.

In terms of process plant layout, an increase in the distance run by streams $i$ and $j$ means an increase in the length of their pipelines. The pipe length for streams $i$ and $j$ to run from their starting points to their endpoints is 4 length units. With the heat exchanger, streams $i$ and $j$*'s* pipe lengths need to be increased by 1 length unit. Thus, we say that the pipe length required for streams $i$ and $j$ to exchange heat is 1 length unit considering each stream individually or 2 length units considering both streams together.

The length of the pipe for the transport of a stream depends on the coordinates of the heat exchanger in the plant and also on the coordinates of the equipment before and after the heat exchanger. In the example shown above, the storage tank is the starting point of stream $i$, and the reactor is the endpoint of stream $i$. Analogously, the separator is the starting point of stream $j$, and the distillation column is the endpoint of stream $j$.

With only the coordinates of the starting points and the endpoints of the streams it is possible to estimate the minimum pipe length required in a heat exchange. This estimate can be carried out by using the rectangular distance between the coordinates of the streams (Pouransari and Maréchal, 2014; Souza *et al.*, 2016; Rathjens and Fieg, 2018). The rectangular distance is the distance measured along the rectangular axes and defined as shown in Eq. (1) for hot stream $i$ with coordinates $(x_i, y_i)$ and cold stream $j$ with coordinates $(x_j, y_j)$.

$$\text{rectangular distance}_{i,j} = |x_i - x_j| + |y_i - y_j| \tag{1}$$

In a number of works, HENs were designed considering the pipe length necessary for a hot and a cold stream to exchange heat. In doing so, it was possible to obtain network typologies less costly in terms of piping and pumping costs. The next section reviews the contributions that considered the pipe length of heat exchange in the synthesis of HEN.

## 2. LITERATURE REVIEW

Pouransari and Maréchal (2014) used the distance between the coordinates of the streams to narrow down the optimal solutions of the heat load distribution problem. The authors defined a single pair of coordinates for each stream and computed the Euclidean distance between them. The Euclidean distance was used as a weight factor in choosing the heat exchanger matches. As a result, the obtained solution prioritised matches between the streams with shorter distances while achieving the minimum or close-to-minimum number of heat exchange units. Based on the solution, Pouransari and Maréchal (2014) estimated the pipe length and piping cost required in the heat exchanges.

Souza *et al.* (2016) designed HENs taking the distance that the streams run to exchange heat into account. Based on the process flowsheet from Shenoy (1995), Souza *et al.* (2016) created a process layout and defined coordinates of the starting points of the streams. It was assumed that to exchange heat, a stream travelled a distance equal to the rectangular distance between its starting point and the starting point of the other stream participating in the heat exchange. Thus, the pipe length required in a heat exchange was defined as twice the rectangular distance between the starting points of the streams. The results showed that by taking the pipe length into account the HEN topology changed.

Rathjens and Fieg (2018) also considered the distance that the streams run to exchange heat in the synthesis of HENs. They used the same arbitrary coordinates presented in the work of Pouransari and Maréchal (2014). In addition, they defined the pipe length required for the streams to exchange heat as twice the rectangular distance between the streams' coordinates. The case studies were solved minimising and not minimising the piping costs. They showed that when the HEN synthesis was carried out minimising the piping cost, matches between the streams relatively closer were prioritised, which modified the pipe routing arrangement.

In all of the mentioned works, the pipe length required in a heat exchange was computed considering a single pair of coordinates for each stream. However, in practice, the streams have two known coordinates, which are the coordinates of the starting points and the coordinates of the endpoints. With this in mind, this work shows that depending on how the equipment is arranged in the plant layout, the use of single coordinates may overestimate the pipe length of heat exchange compared with the case where the coordinates of both starting points and endpoints of the streams are considered.

Furthermore, this work introduces a methodology to estimate the pipe length required in a heat exchange not only by using the starting points and the endpoints but also by using the entire trajectory of the streams as they run from their starting points to their endpoints. This methodology is able to provide results even smaller than those obtained using the starting points and the endpoints solely.

## 3. INCLUDING THE ENDPOINTS OF THE STREAMS IN ADDITION TO THE STARTING POINTS

As mentioned earlier, published works that used pipe length in HEN synthesis estimated the distance required in a heat exchange using a single pair of coordinates for each stream. If the coordinates of the streams correspond to their starting points, then the pipe length required for the streams to exchange heat is twice the rectangular distance between the streams' starting points. However, the endpoints can also be considered. In this way, the rectangular distance can be computed in four ways, with combinations between the starting and endpoints of the hot and the cold streams. The pipe length required in a heat exchange is then the smallest of the four. Figure 3a, Fig. 3b, Fig. 3c, and Fig. 3d depict the rectangular distance computed with the starting points (**SP**) and the endpoints (**EP**) of streams $i$ and $j$, shown as a rectangular area. Any rectangular route between the shown coordinates will have the same length. In this case, the smallest rectangular distance involves streams $i$ and $j$'s endpoints.

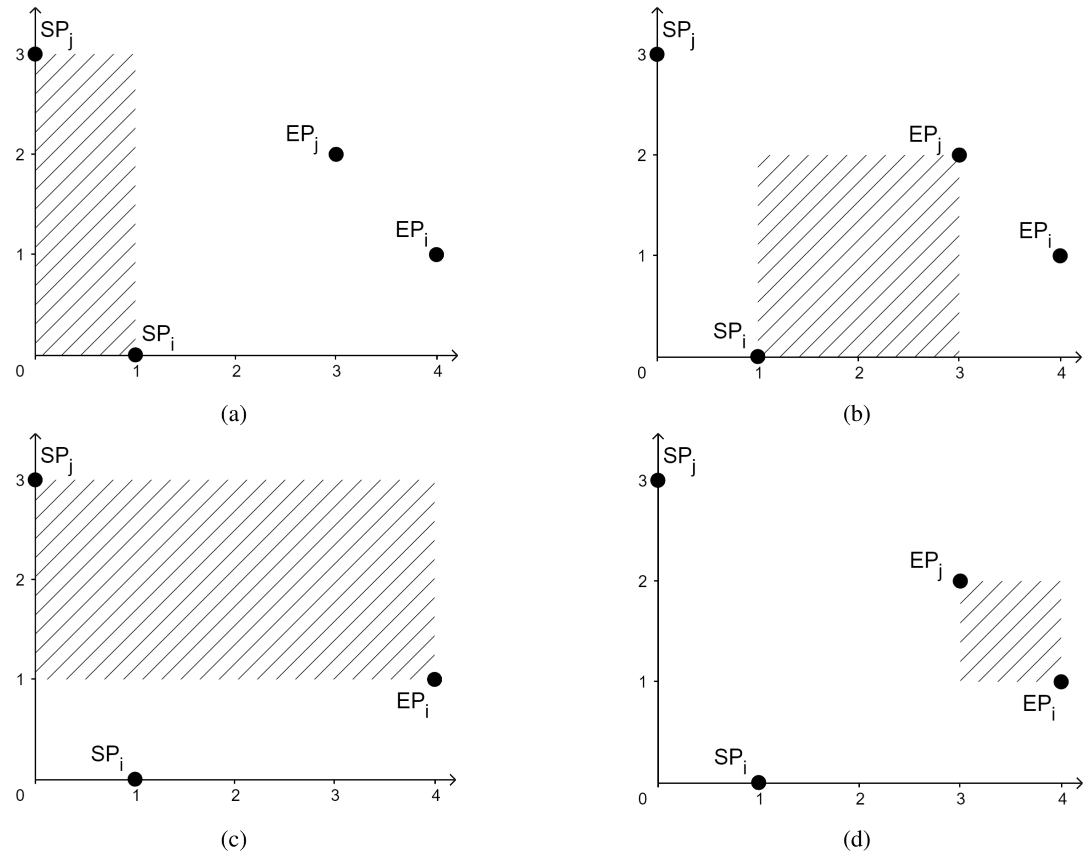


Figure 3: Rectangular distance between: (a) starting points, (b) stream *i's* starting point and stream *j's* endpoint, (c) stream *i's* endpoint and stream *j's* starting point, (d) endpoints.

## 4. SHORTEST LENGTH METHOD

Up to this point, the pipe length required for the streams to exchange heat is estimated based on the rectangular distance between the starting points and the endpoints. However, we noticed that as the hot and the cold streams run from their starting points to their endpoints, they may approach each other. By assuming the heat exchanger is placed in the region where the hot and the cold streams approach each other, the length that the hot and the cold stream have to run to exchange heat is the shortest possible. As a result, the pipe length required for the heat exchange is the shortest possible. Based on this insight, this section presents the Shortest Length Method (SLM), which is developed under the following assumptions:

- the method is developed using the rectangular coordinate system, that is, stream piping is routed along the $x$ or $y$-axis (Van Laan, 1987);
- the distance between two points on the rectangular coordinate plane is measured using the rectangular distance;
- starting points and endpoints represent the nozzles of the equipment.

### 4.1 The Basic Model

Consider the process shown in Fig. 4, in which stream $i$'s starting point has coordinates (1, 0) and endpoint has coordinates (4, 1). As stream $i$ runs from the starting point to the endpoint, it passes through all $x$-coordinates between $x = 1$ and $x = 4$ and through all $y$-coordinates between $y = 0$ and $y = 1$. Any route that takes stream $i$ from the starting point to the endpoint can then be described with the intervals shown in Eq. (2) and in Eq. (3).

$$1 \leq x \leq 4 \tag{2}$$
$$0 \leq y \leq 1 \tag{3}$$

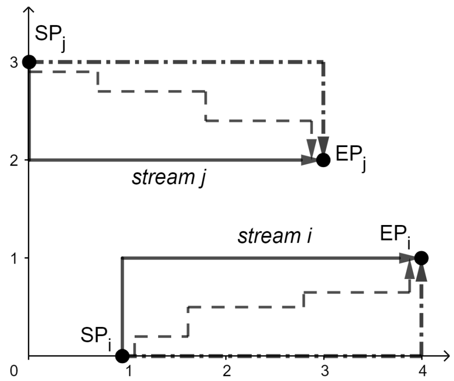


Figure 4: Process with the starting points and the endpoints connected by different routes.

Stream $j$, in its turn, runs from its starting point with coordinates (0, 3) to its endpoint with coordinates (3, 2). As stream $j$ runs, it passes through all $x$-coordinates between $x = 0$ and $x = 3$ and through all $y$-coordinates between $y = 2$ and $y = 3$. Any route that takes stream $j$ from the starting point to the endpoint can then be described with the intervals shown in Eq. (4) and Eq. (5).

$$0 \leq x \leq 3 \tag{4}$$
$$2 \leq y \leq 3 \tag{5}$$

Let us now consider that a heat exchanger has to be placed between streams $i$ and $j$. The heat exchanger must be located in a region of the plant so that streams $i$ and $j$ deviate the least possible from their routes. This can be achieved with the heat exchanger located where streams $i$ and $j$ approach each other as they run from their starting points to their endpoints.

Since the coordinates that streams $i$ and $j$ pass through along the rectangular axes are known, it is possible to infer that streams $i$ and $j$ approach each other in interval $1 \leq x \leq 3$ and that streams $i$ and $j$ approach each other when stream $i$ is at $y = 1$ and stream $j$ is at $y = 2$. Thus, for streams $i$ and $j$ to deviate the least possible from their routes, the heat exchanger must be placed inside the intervals shown in Eq. (6), Eq. (7) and depicted in Fig. 5 as the hatched area.

$$1 \leq x \leq 3 \tag{6}$$
$$1 \leq y \leq 2 \tag{7}$$

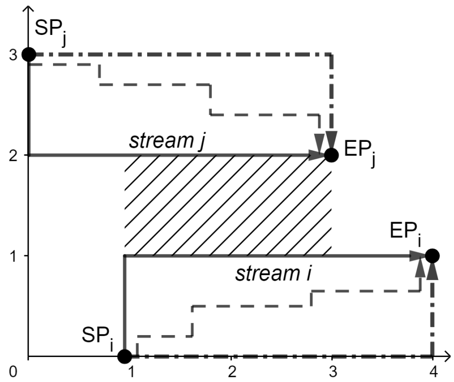

Figure 5: Intervals where streams $i$ and $j$ approach each other.

With the heat exchanger placed in the intervals mentioned above, streams $i$ and $j$ take their routes from the starting points to the hatched area. Once stream $i$ and $j$ are running along the hatched area, they leave their routes and run towards the heat exchanger. Depending on the location of the heat exchanger in the hatched area, stream $i$ may run longer than stream $j$, and vice versa. Nonetheless, as long as the heat exchanger is located inside the hatched area, the distance run by streams $i$ and $j$ together is the same regardless of the heat exchanger's location. Figure (6) depicts streams $i$ and $j$ leaving their routes and running to the heat exchanger, which is assumed to be in the middle of the hatched area.

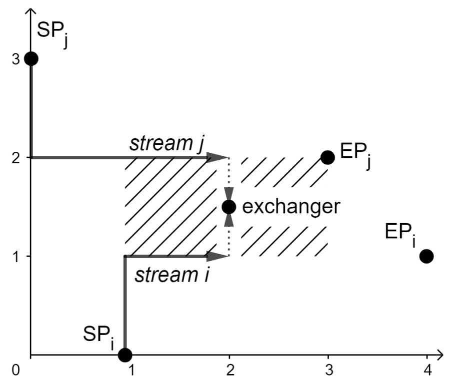

Figure 6: Heat exchanger in the middle of the hatched area.

The distance run by streams $i$ and $j$ together from the point where they leave their routes to the heat exchanger can be estimated. The estimate is carried out by computing the rectangular distance between streams $i$ and $j$*'s* coordinates where they approach each other. On the $x$-axis, streams $i$ and $j$ not only approach each other but also overlap each other as they both pass through interval $1 \leq x \leq 3$. So, they approach each other at the same coordinates, therefore, the distance they run to reach the heat exchanger is zero length units on the $x$-axis. On the $y$-axis, the rectangular distance between the coordinates of streams $i$ and $j$ where they approach each other is given by Eq. (8).

$$\begin{aligned} l_{i,j,y} &= |k_{i,y} - k_{j,y}| \\ &= |1 - 2| \end{aligned} \tag{8}$$

where,

- $l_{i,j,y}$ is the shortest distance that streams $i$ and $j$ run together from their routes to the heat exchanger (the sum of the distances run by streams $i$ and $j$);
- $k_{i,y}$ denotes the coordinate of stream $i$ at the point where stream $i$ approaches stream $j$ on the y-axis, as stream $i$ runs along its route;
- $k_{j,y}$ is analogous to $k_{i,y}$ but applied for cold stream $j$.

Since after exchanging heat streams $i$ and $j$ return to their routes, the result shown in Eq. (8) has to be taken twice. Thus, the shortest distance run by streams $i$ and $j$ to exchange heat is 2 length units. This result can also be understood as the shortest pipe length required for streams $i$ and $j$ to exchange heat.

The procedure shown above can be applied for any heat exchange between a hot and a cold stream with defined coordinates of the starting points and the endpoints in the plant layout. The steps to go through are presented as follows:

1. defining the intervals bounded by the streams' starting points and endpoints;
2. finding the points in the intervals where the streams approach each other;

3. computing the rectangular distance between those points on the $x$-axis and on the $y$-axis, as shown in Eq. (9) and Eq. (10);
4. summing the results obtained from Eq. (9) and Eq. (10) and multiply the sum by 2 to account for the return of the streams to their routes, as shown in Eq. (11).

$$l_{i,j,x} = |k_{i,x} - k_{j,x}| \tag{9}$$
$$l_{i,j,y} = |k_{i,y} - k_{j,y}| \tag{10}$$
$$L_{i,j} = 2\left(L_{i,j,x} + L_{i,j,y}\right) \tag{11}$$

## 5. THE LP MODEL

This section presents the mathematical model to estimate the shortest pipe length required for a hot and a cold stream to exchange heat using the Shortest Length Method. The model is developed for a heat exchanger network with several hot and cold streams. The hot streams are represented by index $i = 1, \ldots, n_i$ and the cold streams are represented by index $j = 1, \ldots, n_j$. Input data is the coordinates of the starting points and the endpoints of the streams in the plant layout and the matches from the heat exchanger network.

### 5.1 Input of the Starting points and Endpoints

The streams have the starting points and the endpoints defined in the process plant layout. The coordinate of the starting point of hot stream $i$ on axis $a$ is denoted by parameter $SP_{i,a}$, and the coordinate of the endpoint of hot stream $i$ on axis $a$ is denoted by parameter $EP_{i,a}$. Analogously, the coordinate of the starting point and the endpoint of cold stream $j$ on axis $a$ is denoted by parameters $SP_{j,a}$ and $EP_{j,a}$, respectively.

### 5.2 Heat Exchanger Network Description

The matches from the heat exchanger network are input into the model by means of parameter $k_{i,j}$, as shown in Eq. (12).

$$k_{i,j} = \begin{cases} 1, & \text{if stream } i \text{ is matched with stream } j; \\ 0, & \text{otherwise} \end{cases} \tag{12}$$

$$i \in \mathrm{H}, \quad j \in \mathrm{C}$$

where, H is the set that contains all hot streams $i$, and C is the set that contains all cold streams $j$.

### 5.3 Coordinates of the Streams

Given the heat exchange between hot stream $i$ and cold stream $j$ expressed by parameter $k_{i,j} = 1$, the coordinate on axis $a$ of hot stream $i$ as it travels to exchange heat with cold stream $j$ is given by variable $m_{i,j,a}$. For hot stream $i$ to reach the heat exchanger, hot stream $i$ must be along the route between its starting point and endpoint. This constraint is applied by Eq. (13) and Eq. (14).

$$m_{i,j,a} \geq \min\left(SP_{i,a}; EP_{i,a}\right) \tag{13}$$
$$m_{i,j,a} \leq \max\left(SP_{i,a}; EP_{i,a}\right) \tag{14}$$
$$i \in \mathrm{H}, \quad j \in \mathrm{C} \mid k_{i,j} = 1, \quad a \in \mathrm{A}$$

where A is the set that contains all axes $a$.

Analogously, the coordinate on axis $a$ of stream $j$ is denoted by variable $n_{j,i,a}$ with the constraints presented in Eq. (15) and Eq. (16).

$$n_{j,i,a} \geq \min\left(SP_{j,a}; EP_{j,a}\right) \tag{15}$$
$$n_{j,i,a} \leq \max\left(SP_{j,a}; EP_{j,a}\right) \tag{16}$$
$$i \in \mathrm{H}, \quad j \in \mathrm{C} \mid k_{i,j} = 1, \quad a \in \mathrm{A}$$

### 5.4 Distance to Heat Exchanger

The distance on axis $a$ run by streams $i$ and $j$ from the point where they leave their routes up to the heat exchanger, $l_{i,j,a}$, is given by the rectangular distance between coordinates $m_{i,j,a}$ and $n_{j,i,a}$. In this model, the rectangular distance is defined as the greatest value from the positive and negative differences between variables $m_{i,j,a}$ and $n_{j,i,a}$, as shown in Eq. (17) and Eq. (18). This formulation is an alternative to the non-linear absolute function.

$$l_{i,j,a} \geq m_{i,j,a} - n_{j,i,a} \tag{17}$$

$$l_{i,j,a} \geq n_{j,i,a} - m_{i,j,a} \tag{18}$$

$$i \in \mathrm{H}, \quad j \in \mathrm{C} \mid k_{i,j} = 1, \quad a \in \mathrm{A}$$

### 5.5 Pipe Length Required for the Streams to Exchange Heat

The pipe length required for streams $i$ and $j$ to exchange heat results from the summation of variable $l_{i,j,a}$ over all the rectangular axes and the multiplication of the sum by two to account for the fact that after the heat exchange streams $i$ and $j$ return from the heat exchanger to their routes. The pipe length required for streams $i$ and $j$ to exchange heat is represented by variable $L_{i,j}$ and shown in Eq. (19).

$$L_{i,j} = 2 \sum_{a \in \mathrm{A}} l_{i,j,a} \tag{19}$$

$$i \in \mathrm{H}, \quad j \in \mathrm{C} \mid k_{i,j} = 1, \quad a \in \mathrm{A}$$

### 5.6 Objective Function

The objective function is defined as the minimisation of the pipe length required for streams $i$ and $j$ to exchange heat summed over all hot streams $i$ and cold streams $j$ of the heat exchanger network, as shown in Eq. (20).

$$\mathrm{Min} \sum_{i \in \mathrm{H}} \sum_{j \in \mathrm{C}} L_{i,j} \tag{20}$$

## 6. APPLICATION OF THE SHORTEST LENGTH METHOD

Three procedures were introduced to estimate the pipe length required for a hot and a cold stream to exchange heat. The first one functions only with the starting points of the streams. The second one performs the computations with the endpoints in addition to the starting points of the streams. The third method is the Shortest Length Method introduced in Section 4. The present section shows the application of the Shortest Length Method and compares the results obtained from it with those obtained from the other two procedures. All the computations are carried out using the General Algebraic Modelling System (GAMS) software version 24.0.2 with CPLEX solver.

### 6.1 Case Study

This case study uses the bio-ethanol-to-gasoline process adapted from Whitcraft *et al.* (1983); Aldridge *et al.* (1984); Serth and Lestina (2014). The process consists of 4 hot streams and 3 cold streams with the main equipment shown in the flowsheet from Fig. 7. The plant layout created for the process with the starting points and the endpoints of the streams is depicted in Fig. 8 with the coordinates summarised in Tab. 1. The streams of the process are matched for heat recovery according to the heat exchanger network shown in Fig. 9. Based on this information, the pipe lengths required for the hot and the cold streams to exchange heat are estimated using the starting points of the streams, the starting points along with the endpoints of the streams, and the SLM.

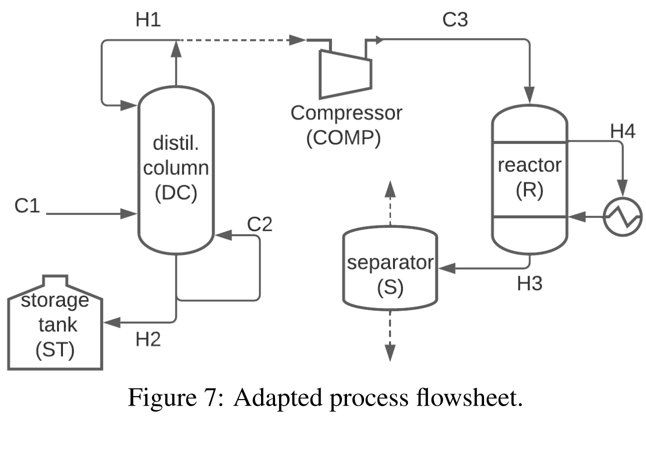


Figure 7: Adapted process flowsheet.

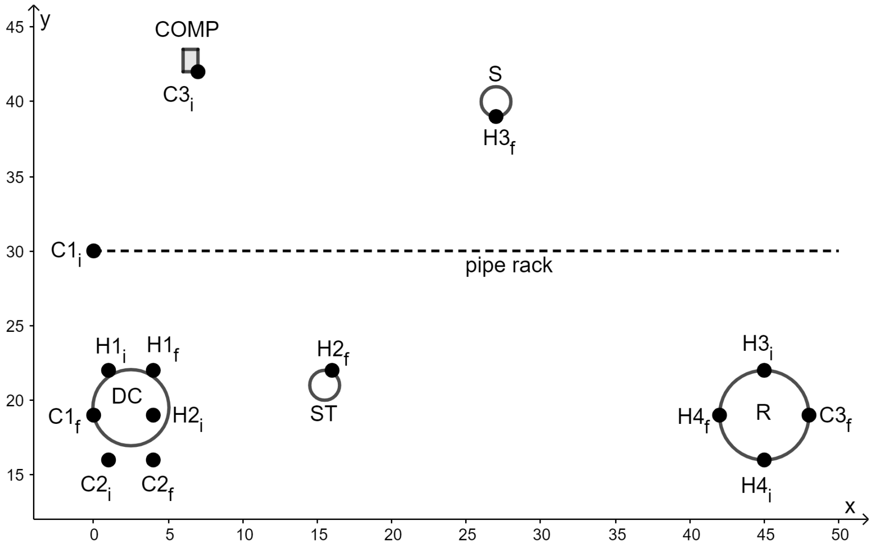


Figure 8: Plant layout created for the process.

Table 1: Starting points and endpoints of the streams.

| stream | $x_{\mathrm{i}}$ | $y_{\mathrm{i}}$ | $x_{\mathrm{f}}$ | $y_{\mathrm{f}}$ |
|---|---|---|---|---|
| H1 | 1 | 22 | 4 | 22 |
| H2 | 4 | 19 | 16 | 22 |
| H3 | 45 | 22 | 27 | 39 |
| H4 | 45 | 16 | 42 | 19 |
| C1 | 0 | 30 | 0 | 19 |
| C2 | 1 | 16 | 4 | 16 |
| C3 | 7 | 42 | 48 | 19 |

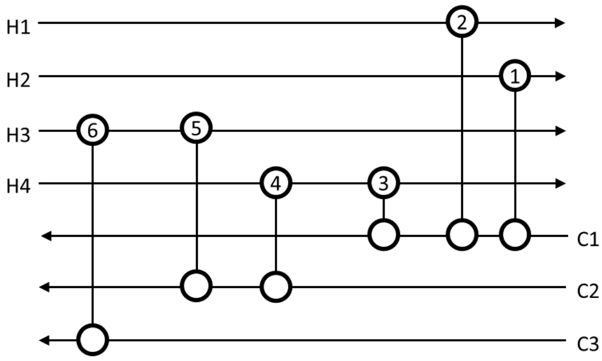


Figure 9: Heat exchanger network.

### 6.2 Results and Discussion

The results show that the summation of the pipe lengths of all the matches is 470 length units estimated considering only the starting points of the streams. When the endpoints of the streams are also considered, this number decreases to 286 length units. With the SLM, this number decreases further to 228 length units. The pipe lengths of the matches shown in the network are presented in Tab. 2.

Table 2: Pipe lengths of the matches shown in the network from Fig. 9.

| stream match | exchanger | using only starting points | using starting points and endpoints | SLM |
|---|---|---|---|---|
| H2-C1 | 1 | 30 | 8 | 8 |
| H1-C1 | 2 | 18 | 8 | 2 |
| H4-C1 | 3 | 118 | 84 | 84 |
| H4-C2 | 4 | 88 | 82 | 76 |
| H3-C2 | 5 | 100 | 92 | 58 |
| H3-C3 | 6 | 116 | 12 | 0 |
| total | | 470 | 286 | 228 |

**Matches H4-C1 and H3-C3**

The results obtained considering only the starting points of the streams show that the heat exchange between streams H4 and C1 requires the longest length of 118 length units. These streams are closely followed by streams H3 and C3 with 116 length units. As the endpoints are considered, the pipe length for streams H4 and C1 to exchange heat falls from 118 to 84 length units, and the pipe length for streams H3 and C3 to exchange heat falls from 116 to 12 length units.

The 12 length units for the heat exchange between streams H3 and C3 result from the distance between the starting point of stream H3 and the endpoint of stream C3. The difference between the pipe lengths considering only starting points and considering starting points as well as endpoints is explained by the equipment arrangement. In the plant layout, the starting points of streams H3 and C3 are located in different pieces of equipment. In contrast, the starting point of stream H3 and the endpoint of stream C3 are located in the same piece of equipment, the reactor. Thus, streams H3 and C3 are closer when they are in the reactor than when they are in different pieces of equipment.

As a matter of comparison, the heat exchange from stream H3's endpoint and stream C3's starting point is 46 length units. The heat exchange from streams H3 and C3's endpoints is 78 length units. This is a typical situation in which neglecting endpoints overestimates the pipe length required for heat exchange.

The results from the SLM show that the pipe length for streams H4 and C1 to exchange heat does not change compared with those using starting points and endpoints. The pipe length of the match H3 and C3 is reduced to zero. This result means that streams H3 and C3 share the same location in the plant layout as they run along their routes.

**Matches H4-C2 and H3-C2**

Stream C2 exchanges heat with stream H4 and then with stream H3. The pipe lengths required for these exchanges estimated only with the starting points of the streams are 88 and 100 length units, respectively. When the endpoints are included in the computation, the pipe lengths necessary for stream C2 to exchange heat with stream H4 and then with stream H3 decrease by 6 and by 8 length units, respectively.

Such reductions in pipe length are not so meaningful as they compare to the distance between nozzles of a single piece of equipment. For example, stream C2 is the boil-up stream of the distillation column, and its starting point and endpoint are located in the distillation column. The distance between stream C2's inlet and outlet nozzles (starting point and endpoint) is 3 length units. Another example can be given with stream H4. This stream circulates the reactor to remove heat, hence, stream H4 starts and ends in the reactor. The distance between stream H4's inlet and outlet nozzles is 6 length units.

By using the SLM, the pipe length required for the heat exchange between streams C2 and H4 decreases again by 6 length units. In summary, the results for the match H4-C2 are 88, 82, and 76 length units. The small reduction obtained with the SLM is explained by the locations of the streams in the plant layout. Since streams C2 and H4 start from and end in a single piece of equipment, they do not run through the plant and consequently do not create regions where their routes come closer or even overlap each other.

The situation is different for the match H3-C2. Stream H3 runs from the reactor to the separator. As stream H3 runs along its route, it approaches stream C2's location in the distillation column. The SLM detects that stream H3 is approaching stream C2 and estimates the pipe length of heat exchange based on where streams C2 and H3 are closest to each other. The result is 58 lengths, 34 length units shorter than that with starting points and endpoints.

**Matches H1-C1 and H2-C1**

The results of the matches H1-C1 and H2-C1 considering only the starting points of the streams are 30 and 18 length units, respectively. When the endpoints along with the starting points of the streams are considered, the pipe lengths necessary for these heat exchanges are reduced to 8 length units both. This result is achieved using stream C1's endpoint and streams H1 and H2's starting points.

From the SLM, the pipe length of heat exchange required for the match H1-C1 decreases further from 8 to 2 length units. The analysis of the routes of streams H1 and C1 reveals that these streams come closest to each other when stream H1 is at its starting point (1, 22) and stream C1 is running along its route, more specifically at coordinates (0, 22).

The result from the SLM for the match H2-C1 is the same as that between stream H2's starting point and stream C1's endpoint, 8 length units. This means that depending on how equipment is arranged in the plant layout, the pipe length required for the heat exchange estimated using the starting points and the endpoints may lead to the shortest pipe length possible.

## 7. CONCLUSION

We began from the concept that in a process plant, the streams run from their starting points to their endpoints. In case the streams need to be heated or cooled, a heat exchanger is installed in the process plant. To reach the heat exchanger, the streams deviate from the routes between their starting points and endpoints. With this in mind, we proposed a method to estimate the pipe length required for the streams to deviate from their routes towards the heat exchanger and to return from the heat exchanger to their routes.

The estimate is carried out with an LP model as follows: given a hot and a cold stream, their starting point and endpoint coordinates are input into the model. With this information, the coordinates of the points existing between the streams' starting points and endpoints are mapped out. Among all these points, the model algorithm detects which are the ones where the streams approach each other. The heat exchanger is assumed to be located somewhere between the detected points. Thus, the rectangular distance between the detected points gives the pipe length required for the hot and the cold stream to exchange heat.

The method proposed in this paper, SLM, was compared with two procedures. These procedures function using the starting points and endpoints solely instead of the entire routes of the streams. The first procedure was extracted from the literature and takes only the distance between the starting points into account. The second procedure is a proposal to include starting-to-endpoint and endpoint-to-endpoint distances. For a heat exchanger network with fixed matches, the procedure extracted from the literature tends to output overestimated results. More accurate estimates can be achieved with the second procedure. The estimate from the SLM is the shortest length possible for a hot and a cold stream to exchange heat.

A weakness of the SLM is that it gives the shortest pipe length possible only when a hot stream exchanges heat with a single cold stream, and vice versa. This characteristic does not undervalue the SLM with respect to the two procedures mentioned in this work. The results from these procedures may be overestimated even when a hot and a cold stream exchange heat only with each other. Another weakness is that the SLM does not provide the coordinates of the heat exchangers in the process plant. As a consequence, the pipe length required for a hot and a cold stream to exchange heat is, strictly speaking, the sum of the pipe lengths of the hot and the cold streams from their routes to the heat exchanger, and from the heat exchanger back to their routes. In other words, the result obtained from the SLM does not provide how many length units a stream needs to exchange heat individually.

Since the SLM requires only the starting point and the endpoint coordinates, the pipe lengths for the streams to exchange heat can be estimated before a HEN is completely designed. In this way, the possible topologies of a HEN can be screened in order to find the one with the lower overall heat exchange pipe length.

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## 10. AUTHORSHIP STATEMENT

The authors are solely responsible for the content of this work.