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Targeting Flowrates and Concentrations in Internal or Total Site Water Mains for Single Contaminant

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This work aims to extend the Pinch-based approach, namely the Material Recovery Pinch Diagram to identify the minimum numbers of water mains/headers required, flowrates and concentrations of the contaminants inside the water mains/headers. The freshwater target should be first determined using the Source and Sink Composite Curves (CC) representations. The header lines can then be drawn along the Source CC to determine the optimal mixing of the water sources that the contaminant limits for the sinks are not violated, while guarantees the freshwater target is still achieved. The attributes of the header lines represent the properties of the headers. The number of segments in the header lines represent the minimum number of headers required, the horizontal length of the segment represent the flowrates inside the water mains and the gradient of the segment is the concentrations of the contaminants inside the header. The methodology can be applied to both process and site-level scale. The approach is flexible for different scenario including single Pinch Point problem, multiple Pinch Points problem and threshold problem. A case study is used to elucidate the proposed methodology. The proposed method is beneficial as it provides a graphical interface for the header targeting and design for the decision-makers. The lengths and gradients of the header lines can also be tweaked by the users as long as the header lines are below the Sink CC.

1. Introduction

The issue of freshwater resource scarcity has raised considerable attention and motivated the material conservation design in various sectors. The water consumptions in the process industry have been increasing in regions, including Europe and Central Asia (UNEP, 2020). This strategic approach of material conservation via systematic Water Integration could help to reduce the reliance on natural resources. Wang and Smith (1994) initialised the targeting approach for wastewater minimisation. Another variation of the tool is proposed by El-Halwagi et al. (2003) and is used for targeting the freshwater and wastewater flowrate. This tool is able to locate the real minimum freshwater target accounting the source mixing options for the single contaminant, while generating the complex water network design. Wan Alwi and Manan (2007) applied the tool for targeting multiple water resources, and later Wan Alwi and Manan (2008) extended the tool for simultaneous target and design with multiple fresh water resources.

Recently, Chin et al. (2020) developed a Pinch-based targeting approach which targets at material recycle/reuse with multiple constraints (e.g. multiple contaminants). Jia et al. (2020) further developed the Water Pinch approach by involving Water Quality and Quantity Pinch and applied to a regional scale to minimise regional water scarcity. For more information on the recent development in Mass Integration, the readers are referred to Klemeš et al. (2018).

The concept of plant-level water mains design was initiated by Feng and Seider (2001) considering single contaminant. For Total Site Water Integration, Chen et al. (2010) proposed a mathematical model for designing the inter-plant water integration schemes with central and decentralised water mains. Fadzil et al.

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(2018) proposed the targeting framework, considering different water header design: one-way and U-shaped two-way header to improve the water reuse network. However, for Pinch-based approach, the number of headers and the inlet limiting concentrations of these headers are usually pre-set or fixed based on certain heuristics. The mathematical approach is also usually a non-linear formulation, which could suffer the computation difficulties in searching optimal global solutions. The decision-makers are not able to inspect and explore the boundaries of the water header design. This work aims to address the gaps by extending the Pinch-based approach to target for the minimum numbers of headers, flowrates and concentrations of contaminants inside each header. The Pinch-based method provides a graphical interface for the decision-makers to design the headers. The users can explore alternative feasible headers' flowrates and concentrations while guaranteeing the freshwater target is still satisfied.

2. Methodology

It is assumed in this work that the water-using processes or units are represented with source-sink representation. The sink is the water demand for the specific units while the source is the water supply outlet from the units. For both fixed flowrate or fixed load operations, the maximum flowrates and the concentrations are used for both sources and sinks. This study aims to extend the Material Recovery Pinch Diagram developed by El-Halwagi et al. (2003) for header targeting. The Source and Sink CC are constructed in a contaminant load vs flowrate diagram, and the Source CC has to be shifted to the right horizontally (pure resource) so that it is below the Sink CC. The amount of shifting denotes the freshwater target for the process. This ensures the contaminant limits (maximum concentrations) for all the sinks are satisfied. Figure 1 shows the classical representation of the Source and Sink CC representation.

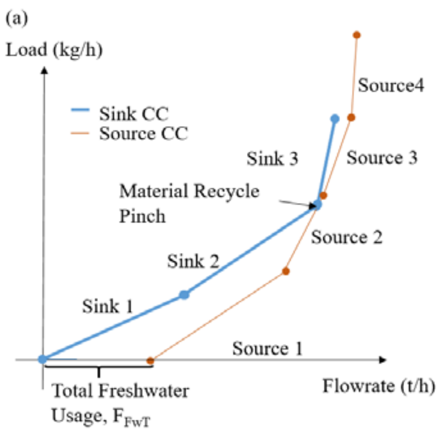

Figure 1: Classical representation of Source and Sink Composite Curves

2.1 Water mains/header targeting for single Pinch Point

The sources can be mixed into the header, and the sinks can be satisfied by the header mix to reduce the water network complexity. However, excessive mixing of the sources could lead to quality deteriorating for the sources, which may result in additional fresh resource intake. Proper header flowrate and concentrations determination is required to ensure the minimum freshwater target is still satisfied. The Composite Curves provide information on source mixing opportunities for the system. Based on Figure 1, it can be seen that for sink 1 and 2, they are fulfilled by a mixture of freshwater, source 1 and part of the source 2. In fact, source 1 and part of source 2 can be mixed together and form a single source header. This is represented in Figure 2.

In Figure 2a, it can be seen that a single header line (red arrow dashed line) can be drawn below the Pinch Point. This header line is made by mixing source 1 and part of the source 2, as shown in the drawings in Figure 2b. In fact, the header line is still feasible, as the total freshwater target identified is still the same. Considering individual source-to-sink allocation, sink 1 may require more freshwater as compared to without header design, but sink 2 requires less freshwater compared to without header design due to mixing of the dirtier and cleaner sources. The total freshwater requirement for both sink 1 and 2 are still identical compared to without header design. In fact, the horizontal length of the header 1 line is the flowrate inside the header, while the gradient is the contaminant concentration inside the header. Similarly, another header line can be constructed dedicated for the sinks above the Pinch (i.e. sink 3). In Figure 2a-b, it can be seen that the header line for sink 3 (header 2) is the remaining source 2 and part of the source 3. For this example, the total no. of headers required is 4 (1 header below the Pinch, 1 header above the Pinch, freshwater header and wastewater header).

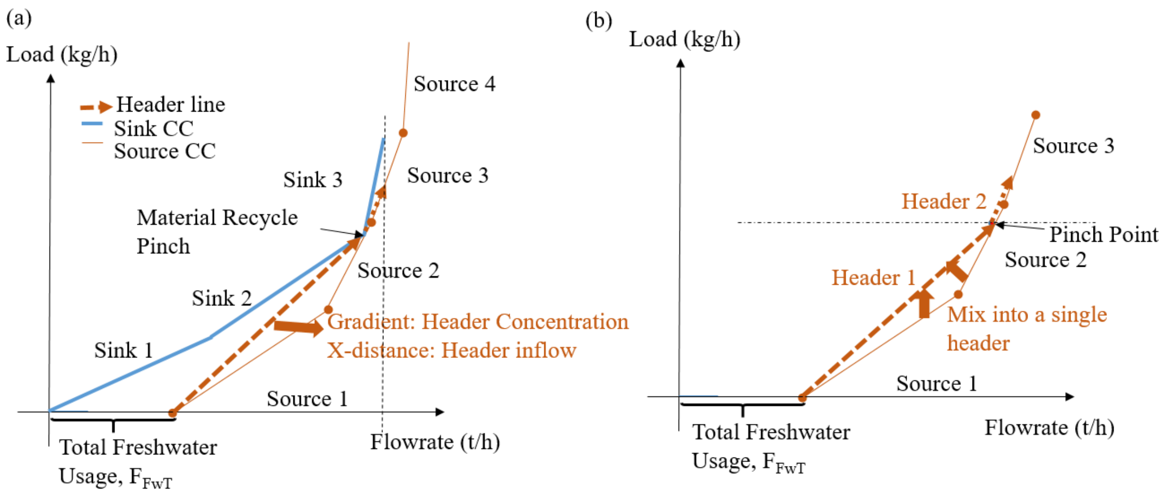

Figure 2: (a) Constructing header line for the illustrative example (b) Allocation of sources to the header

There are certain cases where a single header line below the Pinch Point is not enough. This happens when the header line below the Pinch crosses at the Sink CC- see Figure 3a. This indicates too much mixing of the sources, which decreases the quality of the water sources and require extra fresh resource intake. In this case, another header line can be drawn by splitting the header line below the Pinch into two- see Figure 3b. Notice that the header 1 and header 2 lines in Figure 3b can be at different combinations of lengths. They can be formed by drawing lines along with the Source CC, and ensuring both header lines are below the Sink CC.

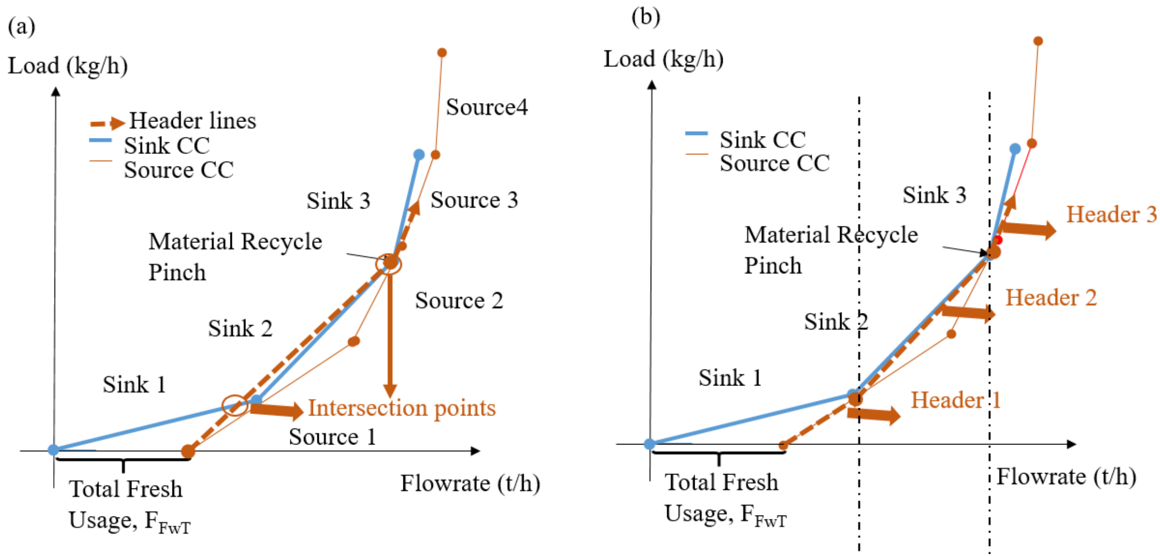

Figure 3: (a) Single header below the Pinch is not enough (b) Another header is drawn by splitting header line

2.2 Water mains/header targeting for multiple Pinch Points

There are certain occasions where there are multiple Pinch Points for the system. Figure 4a shows the Composite Curves representation for such a system. In this case, it is clear that a single header line is not sufficient for the sinks below the Pinch Points. Figure 4b shows the construction of the header lines. A single header line is drawn connecting the Source CC starting point to the first Pinch Point (header 1), and another header line is constructed connecting the First Pinch Point to the Second Pinch Point (header 2).

One can observe that the minimum number of header sources are at least equal or larger than the number of Pinch Points for the system. For example, two Pinch Points indicate at least two headers from the sources are required. If there are no sinks above the Pinch Point, the system in Figure 4 require only two headers from the sources. However, the header lines might intersect at the sink CC as well. If there are any intersections at the header 1 or the header 2 lines, the header lines have to be split until no intersection occurs. As explained in section 2.1, the users are allowed to adjust the split ratio of the header lines at different combination of the headers' flowrates and concentration, as long as they are below the Sink CC.

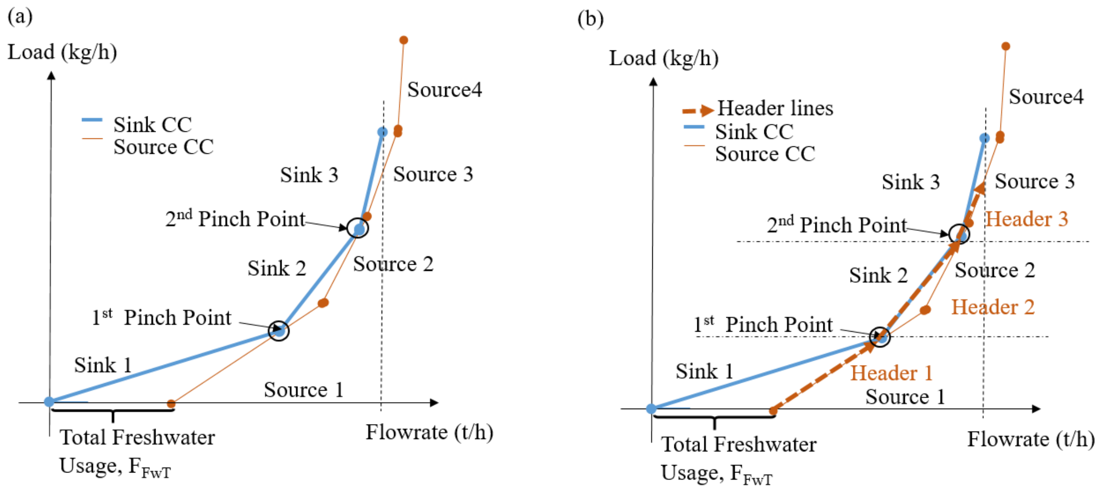

Figure 4: (a) Multiple Pinch Points for an illustrative system (b) Header lines construction for the Multiple Pinch Points problem

2.3 Water mains/header targeting for a threshold problem

There are also possibilities where the system is a threshold problem, i.e. no wastewater generations with or without Pinch Points. Figure 5a shows a scenario when there is no Pinch Point. This happens when the total flowrates of the available sources are less than the total flowrates of the sinks. In such a case, the header line is a mixture of all the sources. Another scenario when there are Pinch Point(s), but no wastewater generations are shown in Figure 5b. Similarly, the header line can be drawn from the Source CC starting point connecting to the Pinch Point. Note that intersection between the header lines and the Sink CC might happen as well.

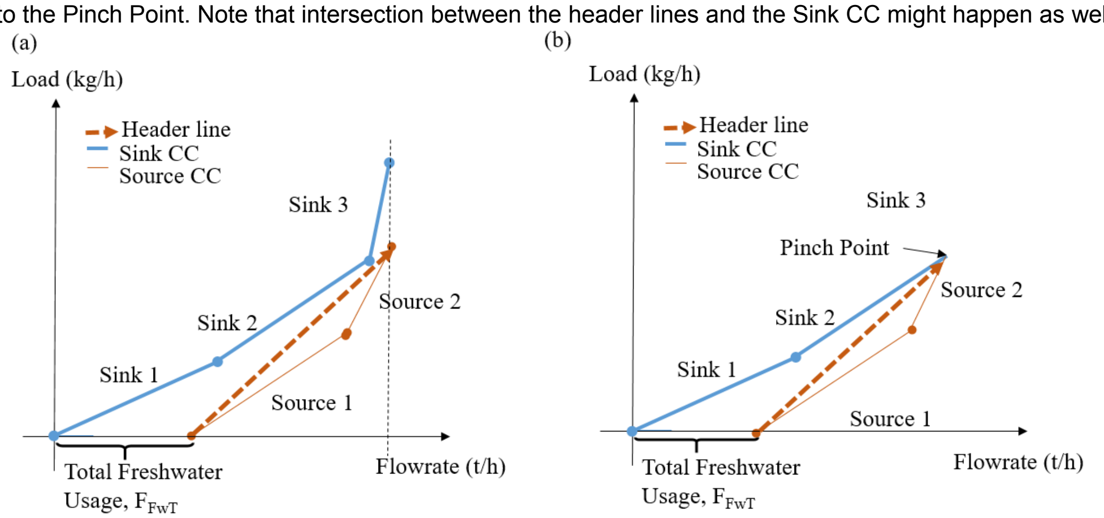

Figure 5: Threshold problem for an illustrative system (a) no Pinch Point (b) single Pinch Point

2.4 Overall procedure

The following procedure for headers targeting using the Composite Curves summarising the conceptual explanations from the previous sections is presented as follows:

a. Construct the Composite Curves for the process/site to determine the freshwater target and Pinch Point(s).
b. Draw a header line below the First Pinch Point, starting from the shifted Source CC initial point and connect to the Pinch Point(s).
c. If there are multiple Pinch Points, connect the Pinch Points with the header lines

d. Draw a header line above the last Pinch Point, starting from the Pinch Point along with the Source CC until the horizontal length matches with where the Sink CC ends. (For single Pinch Point problem, first Pinch Point = last Pinch Point)
e. Check if intersection(s) exists between the header lines and the Sink CC. If there are any, split the header lines, and draw the header lines with any combinations until the entire Header Curve is at the right side of Sink CC.
f. Determine the number of headers (number of segments in the header lines), each header source's concentration (gradient) and flowrates (horizontal length).

Similar concepts can be applied for site-level Water Integration. The Pinch Analysis combining the water sources and sinks from various processes can be grouped together to determine the overall water target. Headers targeting can now be performed. However, this approach assumes no internal integration at the process level. If integration at the process level is performed first, the targeting can be performed for the process before site-level integration.

3. Case study demonstration

A single plant is used to demonstrate the proposed approach. The data required for this study are presented in Table 1, based on Fadzil et al. (2018).

Table 1: Plant data for the case study

Sources	F_{SR} (t/h)	C_{TDS} (ppm)	Sinks	F_{SK} (t/h)	Z_{TDS} (ppm)
SR1	200	50	SK1	200	0
SR2	80	100	SK2	80	50
SR3	80	100	SK3	80	50
SR4	140	150	SK4	140	100
SR5	200	200	SK5	200	120
SR6	200	450	SK6	200	200

The proposed graphical approach is applied to the plant specified in Table 1. Figure 6 shows the Composite Curve representation for plant 1. In Figure 6a, the freshwater target is 206.67 t/h, and it shows that there is one Pinch Point for the process. There is another point with very close distance between Sink and Source CC. Based on the procedures presented in Section 2.4, a header line is first drawn for the sinks below the Pinch Point Note that this scenario is similar to that of Figure 3, where one header line below the Pinch Point is not enough. In this case, the header line is split into two below the Pinch. Header 1 is drawn under the 'close contact' point, and Header 2 is drawn connecting the end point of Header 1 to the Pinch Point. There are no sinks above the Pinch Point. The header 1 crosses at the Sink CC, which indicates excessive mixing of the sources. This means Header 1 needs to be splitted. Figure 6b shows the overall header lines with a total of three header segments from the sources. Header 1 is made up by source 1, header 2 is made up of a mixture of SR2, SR3 and SR4, while header 3 is made up with SR4. The gradients of the header line segments represent the concentration of the headers. The flowrates and the concentrations of each header using the configurations in Figure 6b are: Header 1: (200 t/h, 50 ppm), Header 2: (293.33 t/h, 122.73 ppm), Header 3: (200 t/h, 200 ppm).

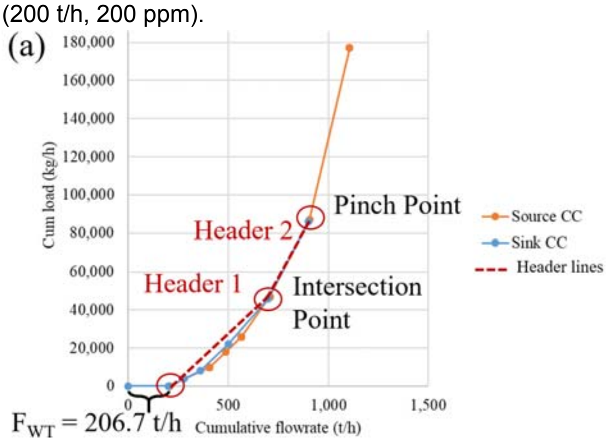

Figure 6: (a) Infeasible header lines (b) Feasible header lines

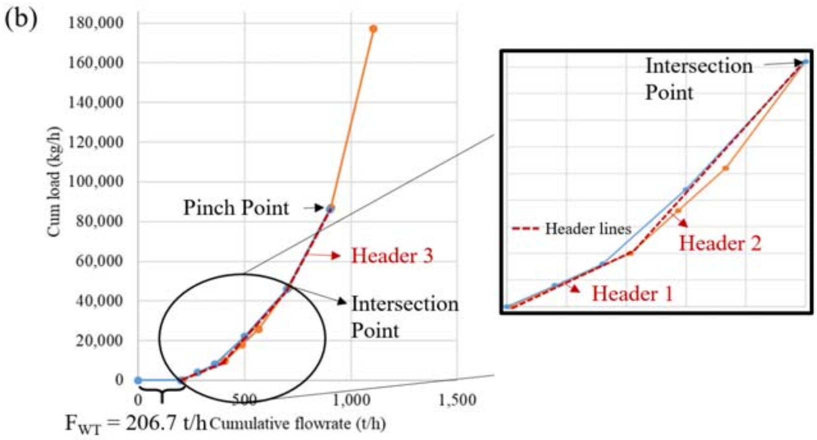

Figure 6: (a) Infeasible header lines (b) Feasible header lines

4. Conclusions

This work has proposed a water mains/headers targeting framework for a single contaminant Water Integration problem. The header lines are constructed by mixing the source segments in the Source CC. Using the Composite Curves representation, the users can target the header source flowrates, the concentration of contaminants inside the header and the minimum numbers of headers required. The graphical interface allows the users to adjust the header lines segments depending on the plant's constraints. A case study is used to elucidate the approach. The results show that the freshwater target is 206.67 t/h, with the identified headers properties: Header 1: (200 t/h, 50 ppm), Header 2: (293.33 t/h, 122.73 ppm), Header 3: (200 t/h, 200 ppm). These headers parameters can serve as the initial points for the mathematical model if more constraints are considered. For future work, the approach can be further developed considering different factors such as economic performance, water regeneration or multiple contaminants problems.

Acknowledgements

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