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MATERIAL PINCH LOCATION AND CRITICAL MATERIALS RECYCLING

Zlatan Mujkić[1+]
Nikita Krekhovetckii[2]
Andrzej Kraslawski[3]

[1]*School of Business and Management, Operations Management and Systems Engineering, Lappeenranta University of Technology, FI-53581 Lappeenranta, Finland*
Email: zlatan.mujkic@lut.fi

[2]*Faculty of Process and Environmental Engineering, Technical University of Lodz, Poland*
Email nikita.krekhovetckii@student.lut.fi

[3]*Higher School of Cyber-Physical Systems and Management, Institute of Computer Science and Technology, St.Petersburg Polytechnic University of Peter the Great, Saint Petersburg, Russia*
Email: andrzej.kraslawski@lut.fi

(+ Corresponding author)

ABSTRACT

Supply of some materials and metals in the World is getting increasingly challenging. To deal with this issue, several organizations (e.g. European Commission) have composed a list of materials critical for the economy, in the list, 27 critical materials (CMs) are included. Furthermore, several actions have been proposed to tackle the problem, including recycling of CM from secondary sources. Global supply chains of raw CMs often rely on limited number of suppliers (e.g., China, Russia, Brazil, US). Since some countries have monopoly and regulate the supply of CMs, they can have big impact on the prices of CM. Therefore, the objective of this paper is to explore the possibility of scrap recycling, which can be used to meet some of the demand. To evaluate the amount of scarp that can be used for recycling, we propose a graphical optimization technique (pinch analysis). To show the applicability of pinch analysis and the amount of scrap that can be recycled, two examples are presented.

Contribution/Originality: This paper contributed in the area of supply chains of critical materials. The methodology used in the paper is Pinch Analysis, which is a graphical optimization method. The methodology used can be useful to determine the potential recycling rates of scrap within supply chain of critical materials.

1. INTRODUCTION

Nowadays, the demand of CMs has increased significantly, since Hi-tech industry are growing rapidly, and consumption of CMs is increasing. To meet the growing demand, efficient management of raw materials is essential to improve economic and environmental performances of supply chains (SCs) and to reduce the consumption of CMs. Additionally, implementing closed-loop supply chain (CLSC) activities (e.g. recycling) is crucial if this goal is to be achieved. The integration and optimization of CM network structure and considering its supplies and demands as whole, can significantly reduce raw material usage.

As of 2017 Blengini *et al.* (2017) list a report with 27 raw materials, which are considered critical. To determine criticality, two parameters are used as benchmark and they are; economic importance (for the European Union) and supply risk. CMs have a wide range of industrial applications (e.g. energy sector, cleaner technologies, electronic parts, aviation and automotive industry) (Peck *et al.*, 2015). Currently, supply rates of CMs are at similar level as demand (Gardner and Colwill, 2018). However, the gap between supply and demand is expected to increase in the

near future, and companies are looking into new sources of CMs (Helbig *et al.*, 2017). One of such possible scenarios, can be implementing reverse management in supply chains (Yao *et al.*, 2018). Even though, there are several prominent concepts of CLSC (Govindan and Soleimani, 2017). In case of CMs, recycling seems most efficient way to recover some of the material (Binnemans *et al.*, 2013). The concept of recycling is not a new idea; however, for it to be successfully implemented in supply chain of CMs, several issues need to be solved (Massari and Ruberti, 2013). Simplified CLSC and flow of materials are presented in Figure 1. Raw materials are extracted, processed and refined into usable materials, which are distributed and used in different products. At the end of the life cycle, scrap of metals are to be collected, stored and prepared for recycling.
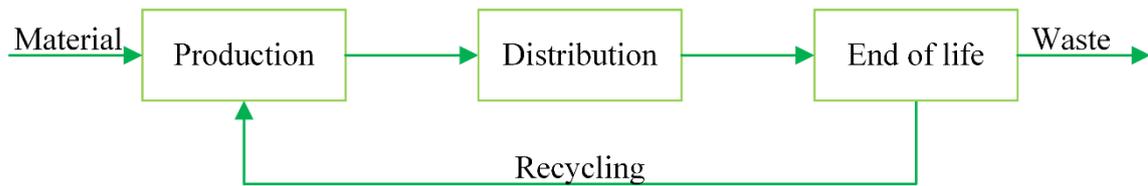

Figure-1. Simplified representation of a closed loop supply chain

In similar way as with heat recovery (Deng *et al.*, 2017) integrating material recovery (El-Halwagi and Manousiouthakis, 1990) with supply chain network structure of CMs, can be an efficient way to reduce requirement for fresh material by minimizing waste. Currently, there are several ways to integrate PA and material recovery into CLSC, namely: graphical (El-Halwagi *et al.*, 2003) algebraic (Almutlaq *et al.*, 2005; Foo *et al.*, 2006) and mathematical programing (Bandyopadhyay, 2015) methods. In this work, graphical method (pinch analysis) is presented. In recent years, pinch analysis (PA) used in several areas, including: CO_2 emission reduction (Harkin *et al.*, 2010) biodiesel production (Sánchez *et al.*, 2011) CO_2 capture and storage (Ooi *et al.*, 2013) energy and heat exchanger networks integration (Gadalla, 2015) sustainable power planning (Priya and Bandyopadhyay, 2017) solid waste management (Jia *et al.*, 2018).

The objective of this paper is to develop a graphical method (pinch analysis) to integrate material recycling and CLSC. For CMs to be recycled, is done first by collecting scrap, which can be from various components and with different fraction ratios. In this way some of the demand can be fulfilled, while the rest can be fulfilled by introducing fresh flow of CM. Additionally, the proposed graphical PA method can also be solved using mathematical programing.

The paper is structured as follows: Section 2, the problem is formulated; Section 3, describes the methodology, In section 4, case studies and numerical results are presented, and finally, in section 5 some findings and conclusions are presented.

2. PROBLEM DEFINITION

SC of CMs can be described as follows: there is certain set of supply flows (sources) $(i) = 1, 2, ..., N\ Source$, and a certain set of demand flows (sinks) $(j) = 1, 2, ..., N\ Sink$. Every source is a stream with a given flow rate, F_i, with a composition, x_i, subject to constrains $C_i\ min$ and $C_i\ max$, and every sink has a given flow rate, F_j, with a composition, x_j, and is subject to constrains $C_j\ min$ and $C_j\ max$. Likewise, external source flows (fresh materials) are available to meet excess demand, and excess waste can be used in recycling process. Given the above description of PA problem, the objective of this paper is to show the potential of CMs recycling, and theoretical threshold for recycle rates.
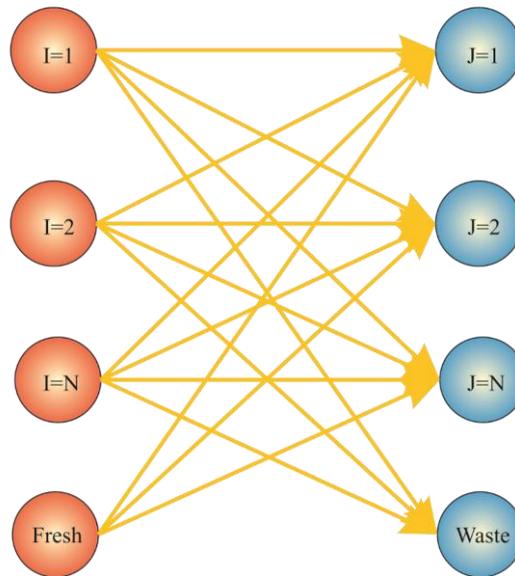
Figure-2. Network structure of material recovery

In Figure 2. a classical synthesis of mass exchange network is presented. However, in our case instead of mass exchanger we use echelons of a SC to present the mass transfer (in this case CM recycling). Material is transferred from source flows to sink flows and the source with the lowest fraction rate is used to meet the requirement of sink with the lowest fraction rate. Likewise, the source with the highest concentration is used to meet the demand with the highest concentration (see Figure 5b). The remaining source flows are considered waste flows due to low fraction of material and can be reused for recycling. While, the remaining sink demand with the highest concentration is fulfilled with flow of fresh material.

3. METHODOLOGY

Heat integration and PA can be presented with composite *curves (see Figure 3). On the* graph composite curve are plotted with hot streams (red) and cold streams (blue). The area where the two curves overlap, heat integration takes place (heat can be reused). On the left-hand side of the graph, hot streams are to be cooled (cooling) down, while on the right-hand side of the graph, cold streams need to be heated (heating). The maximum possible heat recuperation can be calculated based on the minimum temperature difference ($dTmin$) between hot and cold streams. Temperature difference is the driving force in heat recuperation (heat integration), and $dTmin$ can be an optimization variable (see for example (Ravagnani *et al.*, 2005). Pinch Point is the area where hot and cold composite curves are the closest, which is at the minimal temperature difference $dTmin$.
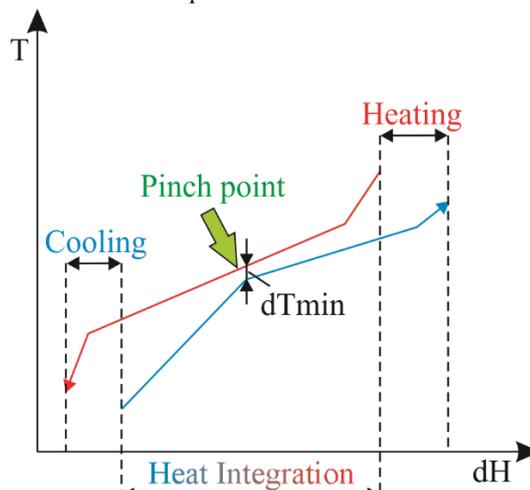

Figure-2. Graphical representation of pinch analysis
Source: Klemeš and Kravanja (2013)

3.1. Graphical Representation of Material Recovery

Similarly, to Heat integration, recycling of CMs can be graphically depicted using PA. In material recovery, hot and cold streams are replaced with source and sink streams (flows) and are represented with red and blue lines, respectively (see *Figure 4a and Figure 4b*). Composite curves are obtained by connecting all flows, starting from the one with lowest, and ending with the one with highest fraction rate. Furthermore, at source curve the fraction rate is decreasing from right to left, while at demand curve the fraction rate is increases from left to right.
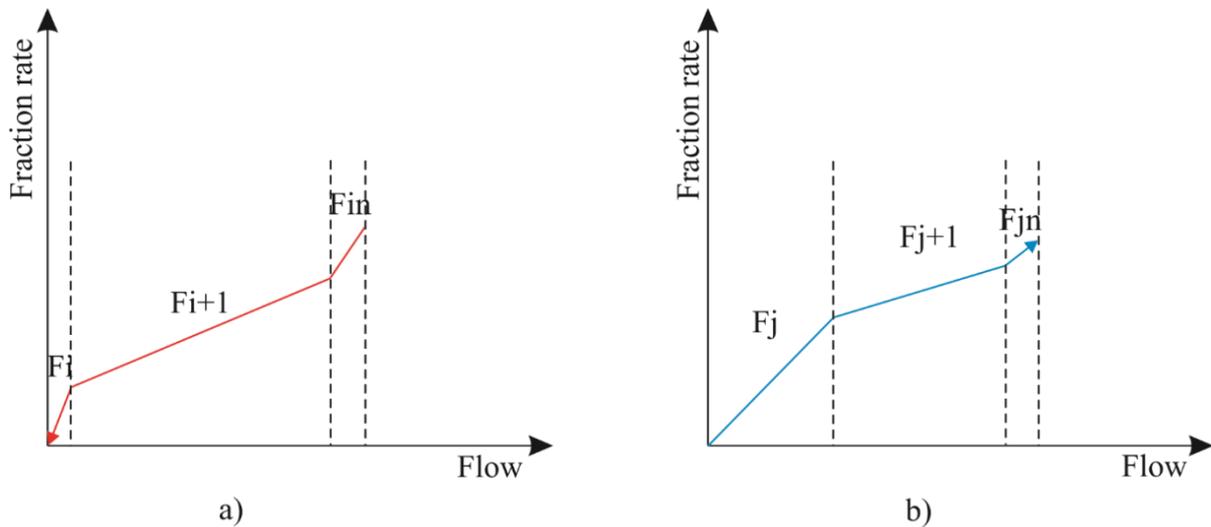

Figure–4. Graphical representation of composite curves for **a**) source **b**) sink

Plotted source and sink curves are presented on Figure 4a and Figure 4b. Combining both source and sink composite curves Figure 5a is obtained. By shifting the demand curve to the right, we obtain the pinch point (see Figure 5b). The area where the source and ink curves overlap represents recovery of a material (part of the supply flows can be used to meet demand), which depends on the material pinch point (difference between fraction rates). In Figure 5b. We have the maximum recycling rate, if the demand curve is shifted to the right, the recycling rate decreases.
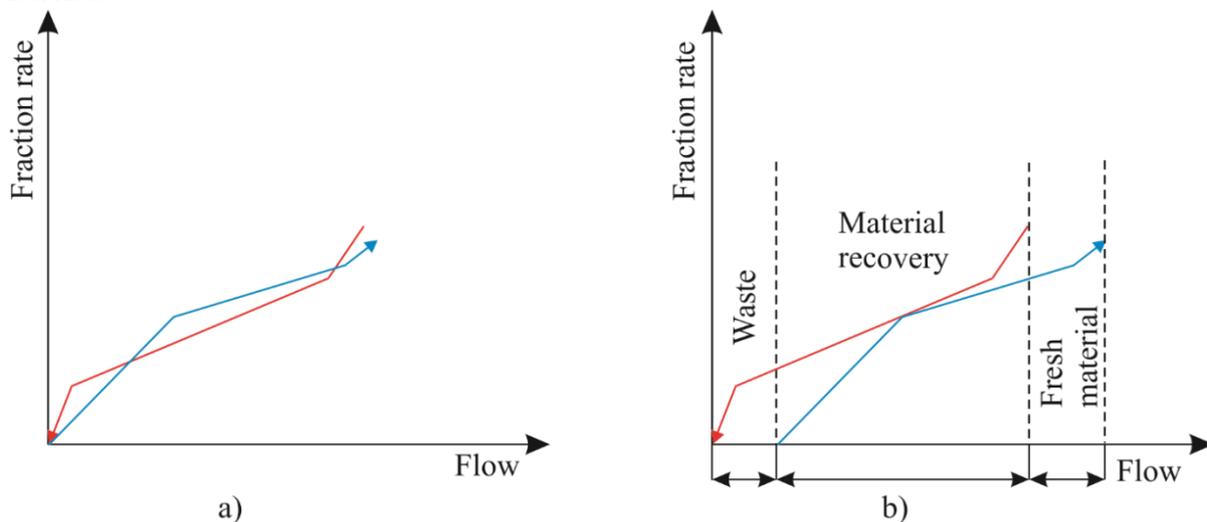

Figure–5.a. Combining source and sink curves **b**. shifting the demand curve to the right

Furthermore, on the right-hand side, there is excess demand, fresh material needs to be added to meet the demand. While, on the left-hand side, there is surplus of material, which is considered waste. However, waste can be returned to the beginning, combined with scrap and reused.

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4. RESULTS AND DISCUSSION

To illustrate potential applicability of PA in CM recycling, two examples are presented. While the first example is illustrative, the second one is an empirical case study of Niobium. In Table 1. data for illustrative example are presented, where ten streams of source and sink are given. Furthermore, flow rates of streams, inlet and outlet fraction rates are presented. Additionally, fresh and waste materials are variables and need to be calculated. Moreover, flows of fresh and waste material are directly proportional to the recycling rate, higher recycling rates reduce the amount of waste produced and fresh material required.

Example 1

The first example is an illustrative case with ten source flows (S1 to S10) and ten sink flows (D1 to D10) and (see Table 1.). Fresh material is almost pure and has the inlet fraction rate over 99 percent, and its outlet fraction rate is not given since it can be calculated. In same way like with fresh material, the flow rates and outlet fraction of waste must be calculated, while the inlet fraction rate is given, because at the beginning of the process there is no waste. Furthermore, the minimum fraction rate difference (material pinch point) is 0. minimum recycling rate required raw material is 224,250 t, which equals the sum of all source flows.

Table-1. Source and demand data for CM recycling problem of example 1

Source	Flow t	fraction in	fraction out	Sink	Flow t	fraction in	fraction out
S1	5000	0.90	0.10	D1	10000	0.20	0.90
S2	10000	0.95	0.05	D2	15000	0.15	0.95
S3	15000	0.70	0.15	D3	20000	0.20	0.70
S4	20000	0.80	0.10	D4	25000	0.10	0.80
S5	25000	0.90	0.10	D5	30000	0.10	0.90
S6	30000	0.80	0.05	D6	35000	0.15	0.80
S7	35000	0.75	0.15	D7	40000	0.15	0.75
S8	40000	0.85	0.10	D8	45000	0.10	0.85
S9	45000	0.95	0.05	D9	50000	0.20	0.95
S10	50000	0.75	0.10	D10	55000	0.10	0.75
Fresh	–	0.99	0.00	Waste	–	0.00	–

Similarly, required demand is 201,750 t, which presents sum of all demand flows. In the case of maximum recycle rate, the flow of raw material is 31,750 t, while the flow of waste is 9250 t.

Table-2. Obtained results for different recycling rates of example 1

*Recycling rate %	Fresh material	Waste material
0	221500	199000
10	211000	188500
20	194500	172000
30	169250	146750
40	141750	119250
50	114250	91750
60	86750	64250
70	59250	36750
80	31750	9250

Furthermore, as shown demand for raw material is reduced to 14,15%, comparing to the initial demand of raw material. Similarly, as with raw material waste produced in the SCs of CM are reduced to 4,5%, compared to initial requirement. Produced waste (excess material) can be mixed with fresh scrap and reused instead of disposing it. However, this can be done if the waste meets required criteria such as: economical potential (profitability), the fraction rate left in the waste is high enough.
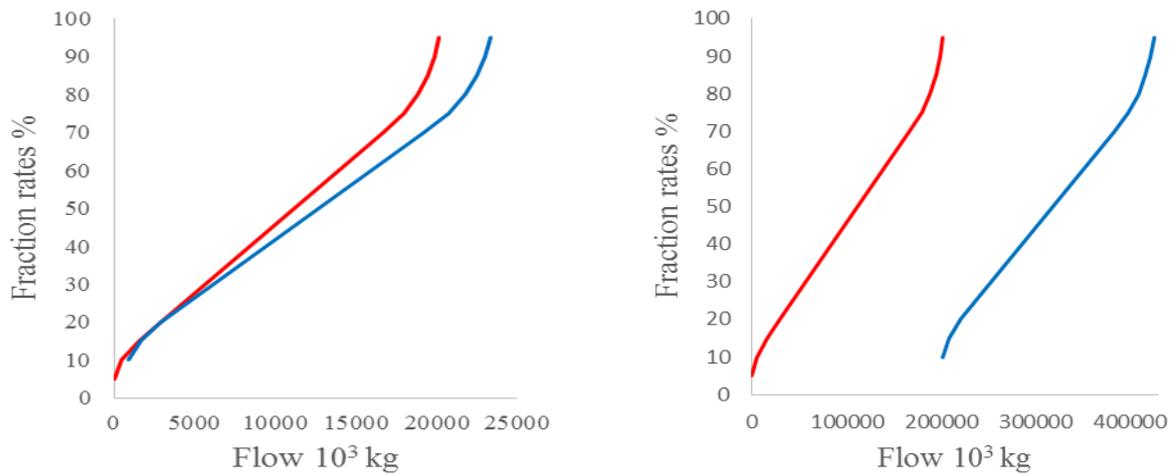
Figure-6. Material pinch point at minimum and maximum recycling rates in example 1

A composite curve diagrams for maximum and minimum recycle rates are presented in Figure 6. For maximum recycle rate we have a minimum fresh material consumed and waste produced. While, for minimum recycle rate is there is maximum fresh material consumed and waste produced.

Example 2

Recycling of any kind of material is viewed as sustainable business practice of future (Zhou *et al.*, 2015) and a potential source of material high in demand (Graedel *et al.*, 2011). Even though, current supply rates of niobium are in balance with demand (Mackay and Simandl, 2014) low recycle rates and supply uncertainty lead to price increase of raw and niobium ores (Mancheri *et al.*, 2018). Therefore, increasing the recycling rates of niobium should be considered in the future (Linnen *et al.*, 2014). Even though, primary producer of niobium is Brazil (Silveira and Resende, 2017) production rates in the 2010s are at similar production level of 70,000 t/year (Alves and Coutinho, 2015). As secondary sources of niobium electronic scrap are most preeminent (Işıldar *et al.*, 2018). However, recycling rates of niobium are somewhat smaller compared to some CMs (Alves and Coutinho, 2015).

For second example, global SC of Niobium is considered with all sources and sinks as shown in Table 3. Region or countries used to present global demand (consumption). Similarly, as with demand, for supply (production) several potential markets are given where the scrap can be collected, as shown on Figure 7. Fresh material is available from raw niobium from three different countries, namely: Brazil (90%), Canada (9%) and the rest of the world (1%) (Nikishina *et al.*, 2014).
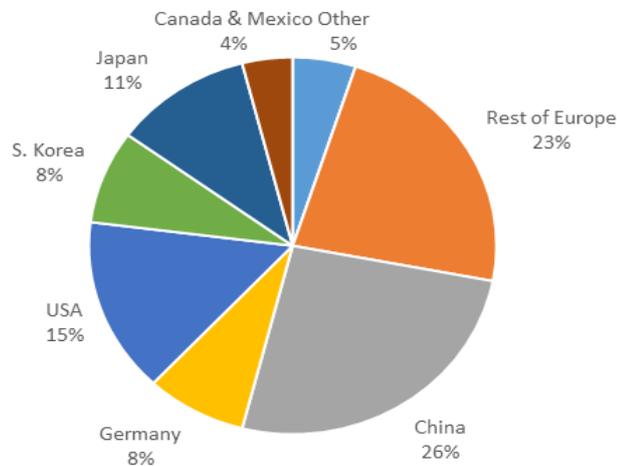

Figure-7. Global annual consumption of ferro-niobium
Source: Montero *et al.* (2012)

According to Graedel *et al.* (2011) niobium is mostly used as ferro-niobium, with grading from 60 to 70%. Furthermore, as reported by Montero *et al.* (2012) total global consumption (demand) of ferro-niobium amounts to ca. 80,000 t annually. The amount of recycled niobium could be as much as 50% (Buchert *et al.*, 2012) and the source of niobium can potentially be wasted electronic components or enriched steel alloys. However, more research needs to be done in the area (Naumov, 2008). Niobium is mostly used for steel alloy, which contains between 0.1% and 1.25% of niobium (Montero *et al.*, 2012) and this is chosen as source fraction rates of scrap. According to Nikishina *et al.* (2014) most of the secondary sources of niobium comes from electronic parts, and reinforced steel containing niobium.

Table-1. Source and demand data for CM recycling in example 2

Source	Flow	fraction in	fraction out	Sink	Flow	fraction in	fraction out
S1	4000	0.6100	0.0010	D1	4000	0.0110	0.6800
S2	6000	0.6900	0.0125	D2	18400	0.0125	0.6300
S3	8000	0.6500	0.0100	D3	20800	0.0010	0.6900
S4	10000	0.6800	0.0110	D4	6400	0.0100	0.6700
S5	1000	0.6200	0.0080	D5	12000	0.0070	0.6100
S6	15000	0.6300	0.0030	D6	6400	0.0110	0.6200
S7	5000	0.6700	0.0050	D7	8800	0.0030	0.6500
S8	2000	0.6400	0.0070	D8	3200	0.0120	0.6600
S9	17000	0.7000	0.0020	-	-	-	-
S10	7000	0.6900	0.0120	-	-	-	-
S11	9000	0.6100	0.0100	-	-	-	-
S12	11000	0.6500	0.0040	-	-	-	-
Fresh 1	58,000	0.9000	-	Waste 1	-	-	-
Fresh 2	5,750	0.9500	-	-	-	-	-
Fresh 3	570	0.9200	-	-	-	-	-

In Table 4. results are presented for second example, numerically. The obtained results are for recycle rate from 0 to 100%. Additionally, on Figure 8. results are presented for recycle rates of 100% (left graph), and for 0% recycle rate (right graph).

Table-4. Obtained results for different recycling rates in example 2

Recycling rate %	Raw material flow kg	Waste flow kg
0	51494	62037
10	46602	57145
20	38602	49145
30	30602	41145
40	22602	33145
50	14602	25145
60	6602	17145
70	0	10543

For recycle rate of 0% total requirement for fresh material is 51,494 t/year of pure niobium, while the demand is 62037 t/year. Similarly, in the case of 100% recycle rate, required fresh niobium is 0 t/year and waste is 10543 t/year. Graphical representation of results obtained in second example are presented on Figure 8.
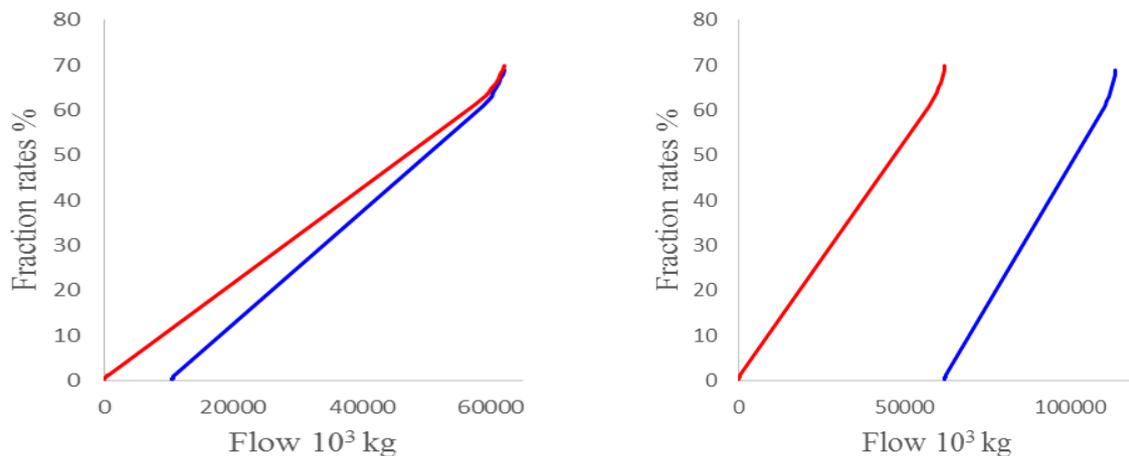
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Figure-3. Material pinch point at minimum and maximum recycling rates in example 2

Similarly, as with previous example maximum and minimum recycle rates are presented on Figure 8. In the case of maximum recycle rate the requirement of fresh material is completely reduced, while produced waste is reduced to 16.99 % from initial requirement. The produced waste can be mixed with other scrap materials and recycled, if the amount of niobium in waste is high enough.

5. CONCLUSIONS

Based on the material pinch methodology, we obtained the following results: 1) material pinch point appears at the point where supply and demand curves cross each other; 2) from the second example it is evident that material PA can be used to determine the amount of scrap and raw material needed to meet the demand for CM; 3) material PA can be used in CM supply chain, which can have positive economic, environmental and social aspects.

Material PA can be used to graphically identify pinch location and quantify amounts of waste, fresh and recycled material. Furthermore, as shown in the first example, PA can be successfully applied in SC and recycling. While, with the second example we showed that in the case study of niobium, required fresh material is reduced to zero, which means that demand is met by using scrap only, while produced waste is 16.99% compared to the case where no scrap is used. Furthermore, if produced waste is justified economically, it can be combined with fresh and recycled scrap. In this work, we only included material flow criteria. However, in future works it is possible to develop mathematical models to include economic, environmental and social criteria. Those criteria can be: optimizing cost of different fresh and scrap material sources (economic criteria), selection of appropriate recycling technology based on environmental footprint (environmental criteria) and potential social criteria.

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