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Material pinch analysis: a pilot study on global steel flows

T. Ekvall, A. Fråne, F. Hallgren and K. Holmgren

IVL Swedish Environmental Research Institute, Sweden
e-mail: tomas.ekvall@ivl.se

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car dismantling

Abstract – Many materials can only be recycled a limited number of times because of physical degradation (paper and board), chemical degradation (plastics), or impurities (several metals). Management of the quality of materials is a key to high long-term recycling rates and, hence, to the sustainable future. This key includes several elements, such as: retaining the quality of materials in the production and use of products; retaining the quality of materials in the recycling processes; and using high-quality materials only when it is required. Pinch analysis is a set of methods to optimize physical flows by taking the quality into account. It was originally developed for minimizing the energy demand in process industries. It has been adapted for optimization also of water and solvents flows. A Japanese research group applied part of the method on flows of steel within Japan and globally. We present a pilot study that illustrates how all the elements of the basic pinch approach can be applied to global systems of material flows. Our material pinch analysis (MPA) distinguishes between three categories of steel applications, each with its own requirements on the material quality: rolled steel, sections and re-bar. Copper in wiring etc. increases the copper content of steel recycled from machinery and eventually restricts the recyclability of the steel in a global system where steel use does not increase. This is important because an MPA is mainly relevant when impurities or other quality aspects restrict the recycling rate. Our quantitative results should not be considered accurate reflections of the reality, because the pilot study is to a large extent based on assumptions and crude data. However, the model gives a first indication that the maximum recycling rate of steel is approximately 80% in a potential future when steel use does not increase, unless technology is improved. A full MPA with more thorough data collection would more accurately define the maximum long-term recycling rate and the minimum quantity of ore-based material. In addition, a full MPA would give information on for what applications ore-based material should be used, and what scrap flows should be discarded rather than recycled. Such information can be important for policy-making aiming at increased resource efficiency. If it is important for policy-making it is also likely to be important to industrial companies that can be affected by policies.

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1 Introduction

1.1 Background

Recycling of materials becomes more important as the demand for materials continues to grow, while the stocks of natural resources dwindle or remain constant. A sustainable future requires a high degree of recycling. However, many materials can only be recycled a limited number of times because of physical degradation (paper and board), chemical degradation (plastics), or impurities (several metals).

Management of the quality of materials then becomes a key to the sustainable future. This key includes several elements, such as:

- retaining the quality of materials in the production and use of products;
- retaining the quality of materials in the recycling processes; and
- using high-quality materials only when it is required.

1.2 Pinch analysis

Pinch analysis is a set of methods aiming at minimising the energy demand in process

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industries [1]. It is based on thermodynamic principles and on the fact that different processes in an industrial plant require different temperature and pressure levels. Pinch analysis describes the optimum utilization of the hot flows that give off heat and the cold flows that needs to be heated. A network of heat exchangers is installed to allow energy to be transferred between these flows. The heat exchanger network is optimised to allow for maximum reuse of the energy within the plant, for example by avoiding the use of high-quality energy in processes where low-grade energy is sufficient.

Analogies between heat and mass transfer led to the field of mass pinch analysis. This has been applied to obtain efficient use of, for example, solvents in industrial plants [2]. Here, the key parameter of the flow is concentration rather than energy and pressure. A related methodology is the water pinch analysis, where the purpose is to optimise water flows in industrial plants [3,4]. The quality of the flows is here given as the concentration of contaminants or the purity of the water.

El-Halwagi et al. [5] presented a general pinch approach to calculate the potential for reuse/recycling and the minimum use of fresh resources. Instead of hot and cold flows they map and arrange sources and sinks of the substance investigated. They describe the quality of the flows in terms of their load of pollutants. The approach of El-Halwagi et al. [5] is sometimes called material pinch analysis (MPA); however, it is more related to the mass and water pinch, because it was applied to flows of water and hydrogen within a single production plant.

Zhao et al. [6] also used the source/sink terminology but describe the quality of the flows in terms of impurity or purity. They optimise hydrogen flows with several kinds of impurities through the use of separated source and sink curves for each impurity. They also describe how impurity deficiency (or excess purity) in one part of the system can allow for increased recycling through the mixing of hydrogen with different levels of impurity. This pinch approach can be generalised to the recycling of substances other than hydrogen.

University of Tokyo applied an MPA approach to investigate the potential Japanese recycling of steel [7–11]. The scope of this study was not an individual production plant, but Japan. The key parameter in their analysis was copper concentration in the steel flows. This was found relevant because copper impurities often restrict the use of recycled steel. Although the method applied was called pinch technology, the study did not distinguish between steel applications, but used a general maximum allowable copper concentration of 0.4% [10]. No pinch point appears to be identified.

In a more recent MPA from the same Japanese research team, Hatayama et al. [12] presented a dynamic MFA and results from a connected MPA of aluminum. This MPA included not only Japan but also China, United States and Europe. The authors concluded that the maximum recycling rate of aluminum in the US and Europe is less than 100% because of alloys in the scrap metal, particularly from old automobiles. However, little detail of the study is presented in the paper. It is, for example, not clear how they defined the quality of the material. Similar to the MPA of steel in Japan, no pinch point was presented.

The Japanese research team also published studies in Japanese (e.g., [13]). The content of these publications was unfortunately not intelligible to the authors of this paper.

To fully utilise the strength of pinch analysis, a pinch analysis of a material should take into account the fact that different processes and products require material with different purity. The geographical scope should be global if the material is globally traded. This is the case not only for steel but also for other metals, paper, etc.

1.3 Purpose and method

This is a pilot study aiming to test if and to illustrate how the basic elements of the pinch approach can be applied to describe the optimum global system of flows for a specific material.

Our case study focuses on steel and can be considered a follow-up on the previous Japanese MPA. We also choose copper

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content as the key quality parameter for steel. Several different metals are used for producing steel alloys. All of these can be found in the scrap from used products. Most of these metals are separated from the steel in the recycling process, but not copper and tin [14]. Unless ore-based steel is added to the system, the copper content in the steel will gradually increase until the material becomes unfit for high-quality applications.

A high copper content means the quality of the steel is lower. We want the quality indicator to be high when the quality of the material is high. For this reason, our quality indicator is the purity of the steel, which we define as the share of the steel that is not copper. Since the copper content is typically less than 1%, the purity will typically be between 99 and 100%.

Since this is a pilot study, the resources available for data collection was limited. The calculations are based on easily available data and, in several occasions, on assumptions.

2 Results

2.1 Material flows

Nakamura et al. [15] distinguish between three categories of steel with different tolerance for copper: maximum 0.1% for hot and cold rolled steel, 0.3% for sections and 0.4% for re-bar (reinforced bars). We use data from Allwood and Cullen [16] to estimate the global use of steel in the year 2008 (1040 Mt) and divide it into these three categories, also including castings in the re-bar category (see Tab. 1). This is a crude simplification of the multitude of steel qualities and applications in the global steel system. However, it is sufficient to demonstrate how the pinch approach can be applied.

We found no data on the quantities of scrap from each of the three steel categories in this tentative study. Instead, we model a hypothetical case where material use has been constant for a long time. The use of steel in new products is then the same as the quantity of steel in old products that are taken out of use.

All steel in products taken out of use is not available as scrap. Part of the steel might be buried underground or in the oceans. Other steel flows might be so diluted or contaminated that recycling is not a realistic option. There can also be material losses in the collection and recycling system. We do not have data on the material losses in the use, collection and recycling of steel, but we assume that it is 5% per recycling cycle for rolled steel and sections, and 20% for re-bar. This means that for each tonne of rolled steel products that reach the end of their use phase, the model assumes that 950 kg will be found in new products after recycling.

We assume, based on the estimate of Kakudate et al. [18] that 4 kg of copper from cables etc. is added to each tonne of steel scrap from machines and similar products (passenger cars, etc.). This resulted in the material flows presented in Table 2.

2.2 Material pinch

The core of the graphical presentation of an energy pinch analysis is composite curves that plot the enthalpy and temperature of all heat sources (physical streams that need cooling or otherwise give away heat) and heat sinks (streams that are and need to be heated) in the industrial plant. In material pinch analysis, the composite curves instead plot the quantity and quality of scrap from different sources and the quantity and quantity demanded for different applications of the material on the global market. Using the terminology of El-Halwagi et al. [5], we call these the source and sink composite curves.

Figures 1 and 2 illustrate how the steel flows in Table 2 can be plotted in diagrams. Figure 1 presents all applications of steel in a sink composite curve, which describes the total steel-demand. Similarly, Figure 2 includes all scrap-supply in a source composite curve.

The minimum distance between the composite curves is the sum of the quality loss in the recycling process (if any) and the minimum safety margin for the quality (if any). To find the pinch point, the two composite curves are placed in the same diagram, and the sink composite curve is shifted horizontally to the right until it is completely below the source composite curve (see Fig. 3). For simplicity we neglect the possible quality

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Table 1. The global use of steel in different applications during 2008. Estimates based on Allwood and Cullen [16] and Takahashi et al. [17].

Steel application	Total steel quantity (Mt)	Steel category	Steel quantity (Mt)
Transport			
Cars and Light Trucks	93	Sections	32
		Re-Bar	38
		Rolled	23
Trucks and ships	28	Sections	10
		Re-Bar	15
		Rolled	3
Industrial Equipment			
Electrical	27	Sections	19
		Re-Bar	0
		Rolled	8
Mechanical	137	Sections	0
		Re-Bar	22
		Rolled	115
Construction			
Infrastructure	150	Sections	36
		Re-Bar	81
		Rolled	33
Buildings	433	Sections	108
		Re-Bar	191
		Rolled	134
Metal Products			
Metal Goods	134	Sections	0
		Re-Bar	67
		Rolled	67
Consumer packaging	9	Sections	4
		Re-Bar	0
		Rolled	5
Domestic appliances	29	Sections	0
		Re-Bar	0
		Rolled	29
Total	1040		1040

loss in the recycling process and the possible minimum safety margin for the quality. This means that the minimum distance between the two composite curves is zero. To be nowhere above the source curve, the sink curve needs to be shifted 250 Mt/year to the right, compared to Figure 1.

Figure 3 shows several things about our tentative model:

- The quantity of recovered steel scrap from machinery etc., which is too contaminated with copper to be directly recycled on its own, is 263 Mt/year. This is the horizontal distance between the lowest points of the two curves.
- The minimum required quantity of ore-based steel is 377 Mt/year. This is the horizontal distance between the tops of the two curves.
- The maximum rate of direct recycling of steel, without mixing of different scrap flows, is 64%: (1040–377)/1040 = 0.638.
- The two curves meet at three places. However, the pinch point is at 99.6% purity, because this is the part of the

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Table 2. The global flows of steel and their copper content in our tentative steady-state model based on Allwood and Cullen [16], Takahashi et al. [17], and Kakudate et al. [18]. The figures are rounded.

	Total steel quantity (Mt)	Cu in products (%)	Scrap quantity (Mt)	Cu added in scrapping (kt)	Cu in scrap (%)	Improved car dismantling	
						Cu added in scrapping (kt)	Cu in scrap (%)
Rolled							
Cars & light trucks	23	0.10	22	88	0.50	22	0.2
Other machinery	152	0.10	145	578	0.50	578	0.50
Other applications	243	0.10	231	0	0.10	0	0.10
Sections							
Cars & light trucks	32	0.30	30	120	0.70	30	0.4
Other machinery	19	0.30	18	72	0.70	72	0.70
Other applications	157	0.30	150	0	0.30	0	0.30
Re-bar etc.							
Cars & light trucks	38	0.40	31	122	0.80	31	0.5
Other machinery	22	0.40	18	70	0.80	70	0.80
Other applications	354	0.40	283	0	0.40	0	0.40
Total	1040		926	1051		803	

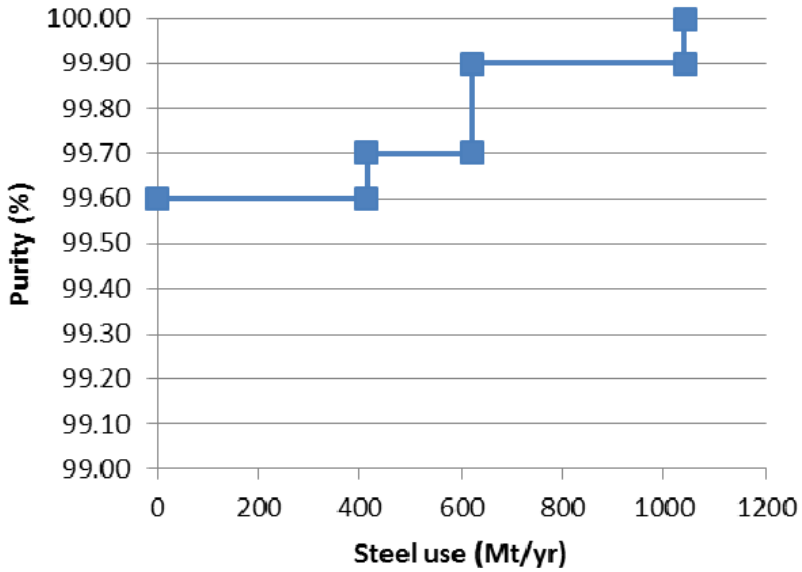


Fig. 1. The sink composite curve of the tentative model, describing the steel demand based on data from Table 2. The term purity here refers to the share of non-copper content in the steel.

scrap-supply curve that decides how far to the right the steel-demand curve needs to be shifted.

In practice, recycling of each separate scrap flow is not realistic. Cast iron and rolled steel will be mixed in the scrapping of, for example, a car. Also, scrap with a high copper content can be deliberately mixed with ore-based steel or high-quality scrap to reach an acceptable copper level, similar to the mixing of hydrogen flows in the pinch analysis of Zhao et al. [6]. This way more scrap can be recycled and the use of ore-based steel can be reduced.

The quantity of extra copper from poor steel scrap that can be tolerated in the recycling system depends on the excess purity in the systems. This is given by Area $A1 + A2 + A3$ between the two curves in Figure 3. With the input data and assumptions above, this excess purity can be calculated to 958 kt copper per year:

$$A1 = 0.001 \times (676 - 546) = 0.131 \text{ Mt/year}$$
$$A2 = 0.002 \times (884 - 695) = 0.378 \text{ Mt/year}$$

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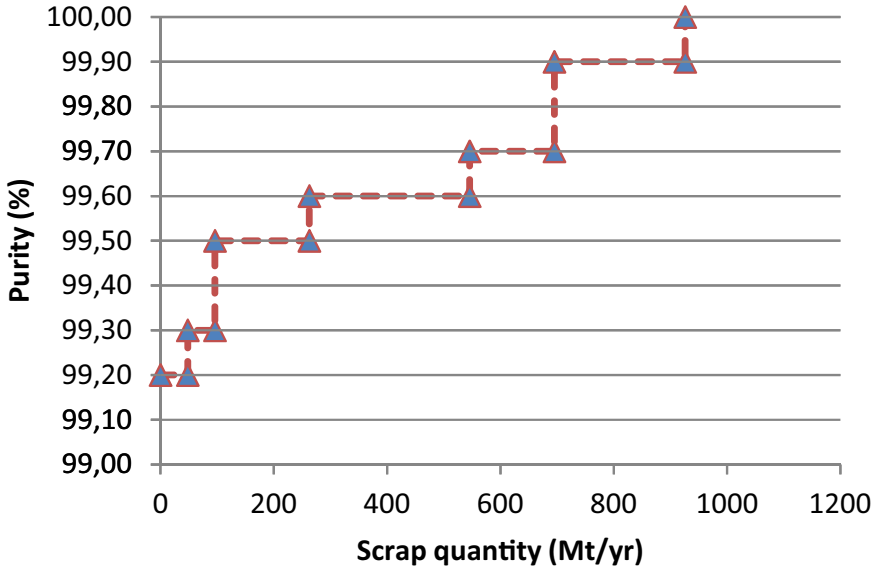


Fig. 2. The source composite curve of the tentative model, describing the supply of steel scrap based on data from Table 2. The term purity refers to the share of non-copper content in the steel.

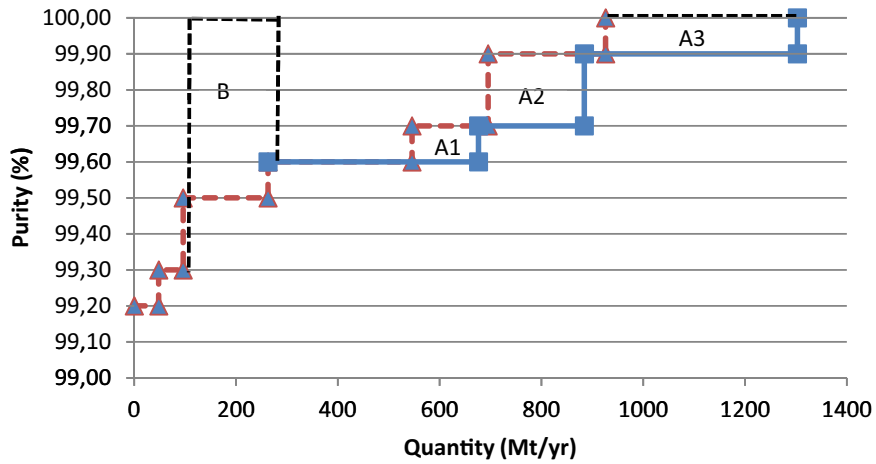


Fig. 3. The pinch diagram of the global steel system. The excess purity is given by the area *A*1 + *A*2 + *A*3.

$A3 = 0.001 \times (1303 - 926) = 0.377$ Mt/year
$A = A1 + A2 + A3 = 0.886$ Mt/year = 886 kt/year.

Area *B* in Figure 3 also corresponds to 886 kt copper per year. This means that the copper content in all rolled steel from machinery etc. is small enough to be accepted into the steel recycling system. All rolled steel from machinery etc. can be recycled, if this scrap is mixed with ore-based steel and high-quality scrap that are available in the optimized system. A small share (16%) of the sections from machinery etc. can also be allowed into this mix.

From these additional calculations, we get the following results:

- The minimum quantity of steel scrap that should be discarded due to high copper content is 89 Mt/year. This is the re-bar and 84% of the steel sections from machinery etc.
- The minimum required quantity of ore-based steel is 203 Mt/year.
- The maximum rate of recycling of steel is 81%: (1040 – 203)/1040 = 0.81.

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These results should be interpreted as crude indications only, because the calculations are based on assumptions and data from single sources. The results of the calculations depend on the material losses in the recycling system. In a sensitivity analysis, we raised the material losses of rolled steel and sections in the use and recycling phases from 5% to 10%. The quantity of steel scrap that needs to be discarded decreased to 75 Mt/year, because the total copper content in the available steel scrap was reduced. On the other hand, the minimum quantity of ore-based steel increased to 220 Mt/year, because more virgin steel is needed to replace the increase in material losses. The maximum recycling rate decreased to 79%.

The results also depend on how much copper is separated from the steel scrap in the scrapping processes. This is demonstrated in next section.

2.3 Improved car dismantling

Cars include many materials but iron and steel is the main constituent. An average car contains 960 kg of steel, and 93 Mt of steel and iron are globally used in the production of cars and light trucks each year [16]. Copper is mainly used in electrical wiring, electric motors, in the steering device and i other electronic and electrical appliances. This means that the copper content of cars has increased over time with increased electrification. The current use of copper in new Volvo cars is between 25 and 30 kg [19].

Improved dismantling of cars is the focus of current research, for example in the on-going Swedish multidisciplinary research project REALIZE (Realizing resource-efficient recycling of cars), which is funded by Mistra (The Swedish Foundation for Strategic Environmental Research).

Our calculations above assumed that 4 kg of copper was added to the each tonne of steel scrap from machines (incl. cars and light trucks) [18]. If the copper content in steel scrap from cars and light trucks is reduced by 75% through progress in the REALIZE project and similar efforts, the total amount of added copper in the steel scrap is reduced by 248 kt (see Tab. 2). This increases the maximum recycling rate in the global steel system from 81% to 83% and reduces the minimum input of ore-based steel from 203 to 180 Mt/year. Such improved dismantling of just cars and light trucks in our calculations reduces the quantity of steel scrap that needs to be discarded by a full 25% (from 89 to 66 Mt/year).

3 Discussion and conclusions

At least two aspects of our tentative MPA on steel need to be discussed. First, the use of steel in new products is in our model the same as the quantity of steel in old products that are taken out of use. This does not reflect the current reality, where global steel use increases. When steel use is much greater than the total quantity of available scrap, the use of ore-based steel is large enough to dilute the copper content to acceptable levels. This means that the copper contamination does not restrict the current recycling.

A material pinch model is more relevant when recycling is restricted by contamination. This indicates that a steel MPA is mainly relevant for investigating a possible future situation where the global use of steel no longer increases.

Second, our tentative MPA is to a large extent based on assumptions and crude data. The quantitative results should not be considered accurate reflections of the reality. Part of the data can probably be significantly improved in a full MPA on steel. However, the investigated system, the global steel flows, is very large and highly complex. Crude simplifications of this system will always be necessary to make an MPA feasible. A full MPA with more thorough data collection would still more accurately define the pinch point of the global steel-recycling system, the maximum long-term recycling rate, etc.

Taking these limitations into account, our pilot study still demonstrates that, with current technology, steel is not 100% recyclable forever. An inflow of ore-based steel is needed to dilute the copper in the steel scrap; otherwise, the copper content will increase to levels that make the steel unfit for use in many applications. In a future when the use of steel no longer increases, copper-rich steel scrap will need to be discarded at landfills or,

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possibly, sent to copper recycling to keep the copper content at acceptable levels.

Even though the numerical results should not be taken at face value, they give a first indication that, again with current technology, the maximum really long-term recycling rate is around 80%. The range was 79–83% in the three different cases we modelled.

The copper-rich scrap that needs to be discarded is in our model represented by re-bar (incl. castings) and sections from machinery. All scrap from applications other than machinery is generated above the pinch point and should ideally be recycled.

The two composite curves in our model run together for most of the interval with re-bar use and scrap from re-bar in non-machinery applications (99.6% purity). This mean care should be taken not to use too much ore-based steel and scrap from rolled steel to produce re-bar; otherwise it might be difficult to find use for all steel scrap from non-machinery re-bar.

Note that a long-term rate of recycling higher than 80% is possible if less material is lost in the use, collection and recycling of steel, and/or if more copper is separated from the steel when machinery etc. are dismantled. As the recycling rate increases, the need for ore-based steel also decreases.

The need to discard copper-rich steel scrap is sensitive to such developments. If less steel is lost in the use and recycling phases, more scrap will have to be discarded because the total quantity of copper in the collected steel scrap will increase. If more copper is separated from the steel in the dismantling processes, on the other hand, the need to discard steel scrap will decrease significantly. Furthermore, improved dismantling can increase also the actual recycling of valuable copper. This could be considered already in the design phase of the product, so that it is easier to separate the different components at dismantling.

Our tentative study takes MPA methodology beyond the material pinch studies that have previously been published in English. It demonstrates that all the elements of the basic pinch approach can be applied to global systems of material flows: constructing the composite curves, identifying the pinch point, and calculating the maximum recycling rate. This allows us to draw conclusions on what flows should not be discarded and on what applications are available for external, virgin flows in the optimized system. The MPA can also be used to calculate how the maximum recycling rate is affected by improvements in the technology that reduces material losses or increases the separation of copper from the steel scrap.

An MPA is mainly relevant when impurities or other quality aspects restrict the recycling rate. It is clearly relevant for steel in a potential future where steel use no longer increases significantly. It is less relevant in a situation where the scrap quantity is far from sufficient to cover the material need, for example because total material use increases rapidly. It is not very relevant for materials such as copper, where recycling processes restores the quality of the material to the same level as virgin material.

The MPA can be applied on materials for which the quality can be measured with a single value. Zhao et al. [6] demonstrate that it can also be applied when there are several quality indicators, as long as a set of composite curves can be developed for each quality indicator. This is the case when the acceptable level of one indicator does not depend on the level of other indicators. An MPA might not be possible to apply for materials for which the quality cannot be measured with a single value if the multiple indicators depend on each other.

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https://doi.org/10.1051/metal/2014043 Published online by Cambridge University Press

References

[1] B. Linnhoff, D.R. Vredeveld, *Chem. Eng. Prog.* **80** (1984) 33-40

[2] M.M. El-Halwagi, V. Manousiouthakis, *J. Am. Inst. Chem. Eng.* **35** (1989) 1233-44

[3] Y.P. Wang, R. Smith, *Chem. Eng. Sci.* **49** (1994) 981-1006

[4] A. Alva-Argáez, A.C. Kokossis, R. Smith, *Chem. Eng. J.* **128** (2007) 33-46

[5] M.M. El-Halwagi, F. Gabriel, D. Harell, *Ind. Eng. Chem. Res.* **42** (2003) 4319-4328

[6] Z. Zhao, G. Liu, X. Feng, *Trans. I Chem. E Part A* **85** (2007) 1295-1304

[7] Y. Matsuno, D. Fujimaki, I. Daigo, Y. Adachi, Integrating LCA with Dynamic MFA and pinch technology for assessing open loop recycling of materials, Abstracts Fourth SETAC World Congress, Portland, 2004, p. 72

[8] K. Hotta, I. Daigo, Y. Matsuno, Y. Adachi, Integration of LCA with material pinch technology, Development of emission minimizing model for industrial symbioses, Abstracts SETAC Europe 14th Annual Meeting, Prague, 2004, p. 201

[9] D. Fujimaki, I. Daigo, Y. Matsuno, Y. Adachi, Integration of LCA with material pinch technology and population balance model, Development of a dynamic model for optimizing environmental impact associated with steel scraps recycling, Abstracts SETAC Europe 14th Annual Meeting, Prague, 2004, pp. 198-199

[10] I. Daigo, D. Fujimaki, Y. Matsuno, Y. Adachi, Development of a Dynamic Model for Assessing Environmental Impact Associated with Cyclic Use of Steel, 2004. http://lca.t.u-tokyo.ac.jp/abst/presentation/2004_1025pinch.pdf

[11] I. Daigo, D. Fujimaki, Y. Matsuno, Y. Adachi, *Tetsu-to-Hagane* **91** (2005) 171-178

[12] H. Hatayama, I. Daigo, Y. Matsuno, Y. Adachi, *Mater. Trans.* **50** (2009) 650-656

[13] H. Yamada, H. Hatayama, I. Daigo, Y. Matsuno, Y. Adachi, *J. Japan Inst. Metals* **70** (2006) 995-1001

[14] S. Nakamura, Y. Kondo, K. Matsubae, K. Nakajima, T. Tasaki, T. Nagasaka, *Env. Sci. Tech.* **46** (2012) 9266-9273

[15] S. Nakamura, Y. Kondo, K. Matsubae, K. Nakajima, T. Tasaki, T. Nagasaka, Supporting Information to [14] http://pubs.acs.org/doi/suppl/10.1021/es3013529

[16] J. Allwood, J.M. Cullen, Sustainable Materials – With both eyes open, UIT Cambridge Ltd, 2012

[17] M. Takahashi, O. Kawano, T. Hayashida, R. Okamoto, H. Taniguchi, High Strength Hot-rolled Steel Sheets for Automobiles, Technical Report No. 88, Nippon Steel, 2003

[18] K. Kakudate, Y. Adachi, T. Suzuki, *Sci. Technol. Adv. Mater.* **1** (2000) 105-116

[19] K. Cullbrand, O. Magnusson, The Use of Potentially Critical Materials in Passenger Cars. Report No. 2012:13. Department of Energy and Environment Division of Environmental Systems Analysis. Chalmers University of Technology, Gothenburg, Sweden, 2012

https://doi.org/10.1051/metal/2014043 Published online by Cambridge University Press