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Material Pinch Analysis

A pilot study on global steel flows

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Summary

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. It might not be possible to apply the pinch approach at all when the critical quality aspect(s) cannot be measured with a single indicator, such as the copper content, or with indicators that are mutually independent.

Our MPA indicates that steel scrap from old machinery is too contaminated with copper to allow for recycling, unless it is mixed with high-quality scrap or with ore-based steel. To achieve maximum recycling, all scrap from applications other than machinery should be recycled, even in a potential future when steel use does not increase. Ore-based steel should in such a future only be used to displaced scrap from machinery that cannot be mixed with high-quality scrap and be recycled. Care should be taken not to use too much ore-based steel and scrap from rolled steel to produce re-bar.

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, it demonstrates that a full MPA with more thorough data collection would define the pinch point and the maximum recycling rate. In addition, a full MPA would give information on the minimum quantity of ore-based material, 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 and, hence, also to industrial companies that can be affected by such policies.

The MPA is one of the tools that might be used in the ongoing project DYNAMIX within the EU 7th Framework Programme. The purpose of this EU project is to develop and assess European policy for increased resource efficiency.

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.

Metals and steel

Metals are extracted from the earth's crust and are widely used in various applications due to its unique characteristics. A number of metals are classified as geochemically scarce even though the extraction rate remains at a high or even increasing level. For some metals the so-called peak production is already expected to have occurred or is likely to occur within a few decades (Ayres et al. 2003). A high degree of material recycling is motivated for other purposes than saving metals resources. Considerable energy savings can also be made, contributing to a decrease in environmental impact due to the fact that material recycling of metals uses less energy than that of virgin production.

In order to economise with valuable materials such as metals it is necessary to use the material in adequate applications where substitution is difficult or not possible. A material of high quality should be used in applications where the quality is best needed. It is also essential to recycle the material as efficiently as possible.

Steel is an alloy consisting of iron (typically more than 98 percent) and carbon (less than 2 percent). Iron ore, composes about 5 percent of the Earth's crust and is mined in about 50 countries. Most iron ore is extracted in Brazil, Australia, China, India, the US, and Russia (World Steel Association, 2011a). In 2010 the global production of crude steel was higher than ever before and exceeded 1400 million tonnes, compared to 850 million tonnes in 2001 (World Steel Association, 2011b).

Steel can either be produced from iron ore or from steel scrap. In 2008, 475 million tonnes of steel scrap were re-melted and used in the production of new steel (World Steel Association, 2010). The two main crude steel production routes are the integrated steel making route based on steel production from blast furnace (BF) or basic oxygen furnace (BOF), and steel production from electric arc furnace (EAF). In the first of routes a mix of iron ore, coal, limestone and steel scrap are used as input materials whereas the EAF route use mainly steel scrap as input.

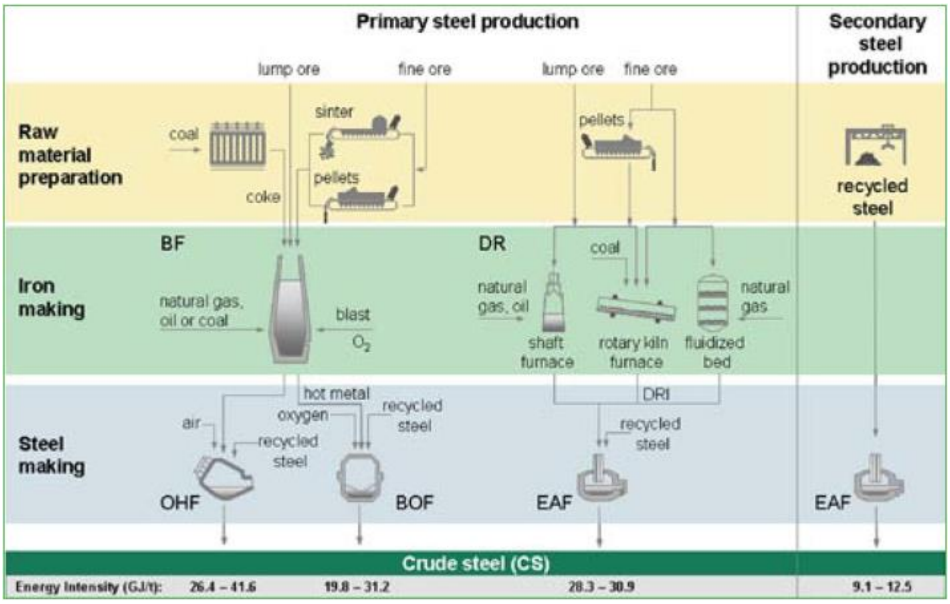

Figure 1. The two steel production routes (World Steel Association, 2011a).

Steel scrap can be divided into “home scrap” (from excess material in steel facilities and foundries), industrial scrap (from downstream production processes) and post-consumer steel scrap (obsolete scrap). According to the World Steel Association (2011a) about 80 percent of the post-consumer scrap is being recycled. This scrap mostly originates from construction, automotive, machinery and electrical and domestic appliances.

Steel could in principle be recycled an indefinite number of times without losing its characteristics. However, impurities such as copper, tin, molybdenum and nickel can reduce the quality of the recycled steel. The most problematic impurities are metals nobler than iron e.g., copper and nickel. These elements are often remains of stainless steel scrap (Jernkontoret, 2003).

Pinch analysis

Pinch analysis is a set of methods aiming at minimising the energy demand in process industries (Linnhoff & Vredeveld 1984). It is based on thermodynamic principles and on the fact that different processes in an industrial plant require different temperature and pressure levels. A network of heat exchangers is installed to allow energy to flow between processes. The heat exchanger network is optimised to allow 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. The heat exchangers can also be combined with heat pumps that raise the temperature and/or pressure of low-grade energy flows.

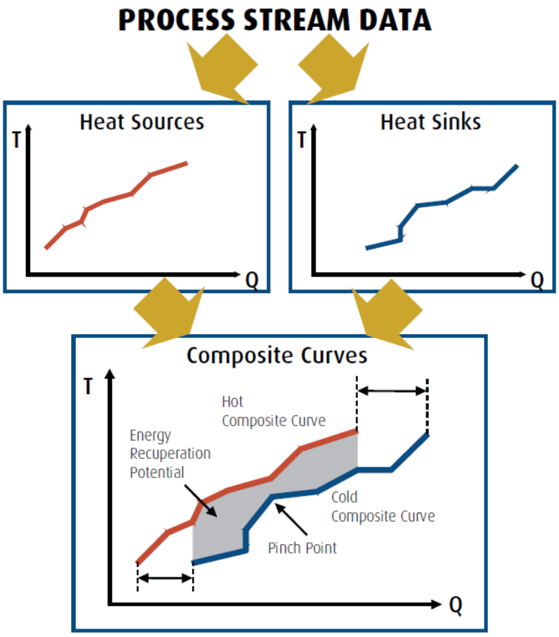

Figure 2. A principal tool in energy pinch analysis is the graphic representation of composite curves (Natural Resources Canada, 2003).

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 (El-Halwagi & Manousiouthakis 1989). 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 (Wang & Smith 1994, Alva-Argáez et al. 2007). The quality of the flows is here given as the concentration of contaminants or the purity of the water.

University of Tokyo developed material pinch analysis (MPA) and applied it to investigate the potential Japanese recycling of steel (Matsuno et al. 2004, Hotta et al. 2004, Fujimaki et al. 2004, Daigo et al. 2004 and 2005). 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, no pinch point appears to be identified.

To fully utilise the strength of pinch analysis, the MPA should take into account the fact that different processes and products require material with different purity. The MPA at University of Tokyo was simplified in the sense that it did not distinguish between steel applications, but used a general maximum allowable copper concentration of 0.4% (Daigo et al. 2004).

The system boundary of the MPA was the national boundaries of Japan. This is also a simplification since steel, like many other materials, is globally traded. Igarashi et al. (2007) observed that steel scrap trade with other Asian countries can significantly affect the quality of Japanese steel.

This Japanese case illustrates that there is a significant potential for further development of MPA. If possible, the geographical scope should be global, and the MPA should take into account the different quality requirements of different processes and products. Refining processes, designed to remove impurities, can also be included in the analysed systems. These will correspond to the heat pumps in conventional pinch analysis.

An important challenge in MPA is that it is difficult to identify a one-dimensional parameter that quantifies the quality of the material. If successful, however, the MPA results indicate the maximum level of recycling for different materials, possibly under different assumptions regarding available refining processes. They also give insights on what is required to approach the maximum recycling level.

1.2. Purpose

This project is a pilot study with the aim to further investigate the possibilities and limitations of MPA, and to prepare for an application for research funds in this area.

The project includes three different parts, each of which is presented in a subsequent chapter:

A. Literature study to learn more about different pinch applications and related research, and to look for more and more recent MPAs. The results are summarized in Chapter 2.

B. Tentative case study to test if and to illustrate how the elements of the pinch approach can be applied to describe the optimum global system of flows for a specific material. This case study is reported in Chapter 3.

C. Development of application or a basis for an application, depending on whether there is a relevant call. Two applications and their outcomes are presented in Chapter 4.

The tentative case study was initially intended as an MPA of copper. However, we soon realized that MPA is not effective for copper because the quality of the copper is restored each time it is recycled. The recycling process is electrolysis and this allows for the production of pure copper, similar to virgin copper. The main difference in quality is due to the different producers and their equipment and not to the number of times the material has been recycled.

Instead, the tentative case study focused on steel and became a follow-up on the previous Japanese MPA. Steel is more suitable for pinch analysis since some of the unwanted material added to steel is not removed in the recycling process. It is merely diluted with other recycled steel of other properties, pig iron and additives to meet properties wanted for the new steel. This makes it possible to analyze and discuss the maximum long-term recycling level.

2. Related research

2.1. Material flow analyses of steel

A major research programme “The steel eco-cycle” was recently completed in Sweden. It dealt with the entire life cycle of steel. Part of the research was an analysis of the steel flows in Sweden (Tilliander et al. 2012). The researchers regarded the recycling system as a machine that controlled or at least lubricated by legislation, taxes, etc. (Gyllenram et al. 2009). If the recycling system could actually be controlled like a machine, an MPA would be very useful since it models and describes the optimum flows.

The European Confederation of Iron and Steel Industries developed a material flow analysis (MFA) of steel in Europe (Eurofer 2007). However, they did not find sufficient data to accurately determine the recycling rates.

Allwod (2012) compiled information on the global flows of aluminum and steel. This information is useful for our tentative MPA. We want it to have a global scope, because the steel markets are global (see Introduction).

2.2. Pinch analysis

Linnhoff March (1998) published a clear description of the basics of energy pinch analysis in a textbook. This textbook is our guide in the tentative case study (see below). However, we have to translate the terms and methodology from energy pinch to material pinch.

The literature study revealed even more applications of pinch analysis than the ones listed in the Introduction. El-Halwagi et al. (2003) presented a general pinch approach to calculate the potential for reuse/recycling and the minimum use of fresh resources. Instead of hot and cold composite curves, they use the concepts of source and sink composite curves. The quality of the flows is described by their load of pollutants. The approach of El-Halwagi et al. (2003) 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. (2007) also used the source/sink terminology but describe the quality of the flows in terms of impurities 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.

Tan & Foo (2007) showed how pinch analysis can be used to investigate how much carbon neutral energy sources are needed to meet a specific emission target in a country or region. Instead of temperature and energy on the axes of the pinch diagram, they plotted the energy demand and CO_2 limit.

Singvhi et al. (2003) and Folorunso et al. (2011) demonstrated how pinch analysis can be applied to virtually any product in supply chain management. Instead of heat sources at different temperatures, the pinch analysis includes a curve that represents the production or supply of the product at different points in time. Instead of heat sinks at different temperatures, the pinch analysis includes the demand for the product at different points in time.

We also found a more recent MPA from the Japanese research team. Hatayama et al. (2009) 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 one-dimensional parameter that quantifies the quality of the material. Similar to previous MPAs, no pinch point was presented.

2.3. Other related research

Kakudate et al. (2000) presented a model of the steel flows in Japan and accounts for copper contamination of the steel. They distinguish between virgin and recycled steel, but include two categories of steel application only: construction and machinery. They state that recycled steel is primarily used for construction. They also state that copper contaminates the steel mainly in the collection of post-consumer scrap, and estimate that 4 kg of copper contaminates the flow for each ton of steel recycled from old machinery.

3. Case study: steel pinch analysis

3.1. Method

Translating pinch terminology from energy to materials

For guiding the MPA, we use the textbook of Linnhoff March (1998). This textbook presents the traditional energy pinch analysis, and we have to translate the method into a terminology that is relevant for material pinch analysis.

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 and/or can be cooled) and heat sinks (streams that need to be heated) in the industrial plant (see Figure 2). Data on the temperature and enthalpy of the heat sources provides the basis for the hot composite curve. The corresponding data on the heat sinks provides the basis for the cold composite curves.

To investigate the potential for energy recovery through heat exchangers, the cold composite curve is shifted to the left in the diagram to come close to the hot composite curve. The distance between the curves should represent the minimum temperature difference needed over a heat exchanger.

The horizontal distance between the top of the curves represents the minimum quantity of high-quality energy that needs to be added to the plant. The horizontal distance between the bottom of the curves represents the minimum quantity of residual or waste heat from the plant.

The point with the minimum distance between the curves is called the pinch point. To obtain the maximum energy recovery and minimize the use of external, high-quality energy, none of this energy should be added to a heat sink below the pinch point. Also, no heat from a heat source above the pinch point should be transferred to a heat sink below the pinch point. Finally, no external cooling should be done above the pinch point. Violating any of these rules will increase the need for external, high-quality energy.

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. (2003), we call these the source and sink composite curves. In this case study on steel, they can also be called the scrap-supply and steel-demand composite curves.

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). If there is no quality loss in the recycling process and no need for an extra safety margin, the distance between the curves at the pinch point is zero.

The horizontal distance between the top of the curves represents the minimum quantity of virgin material that needs to be added to the global market. The horizontal distance between the bottom of the curves represents the minimum quantity of scrap that needs to be deposited at landfills or similar.

To obtain the maximum recycling rate and minimize the use of virgin material, no virgin material should be used for an application below the pinch point. Also, no scrap from a source above the pinch point should be used for an application below the pinch point. Finally, no scrap from a source above the pinch point should be deposited. Violating any of these rules will increase the need for virgin raw materials.

The MPA procedure

We conduct the tentative MPA in four steps:

1. A measure of the material quality is defined.

2. Quality requirements are defined for different applications of the material.

3. Data on the global material flows are collected to investigate where the material is used and what the current quality is in different flows of the material.

4. The MPA is carried through to describe optimum global flows of the material and to quantify the maximum recycling rate.

3.2. Results

The quality indicator

Just like the earlier Japanese study (e.g., Matsuno et al. 2004) we choose copper 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 (Nakamura et al. 2012). Copper from cables etc. is also added to the steel scrap flow (Kakudate et al. 2010). 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%.

Quality requirements

Steel is used for many different applications. Nakamura et al. (2012) 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).

Material flow analysis

We use data from Allwood & Cullen (2012) to estimate the global use of steel in the year 2008 (1040 Mtonne) and divide it into rolled steel (406 Mtonne), sections (208 Mtonne) and re-bar (426 Mtonne) (see Table 1).

We found no data on the quantities of scrap from each of these 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. This might be the case sometime in the future. Currently, however, steel use increases. The use of steel in new products in 2008 was probably greater than the quantity of steel in old products that were taken out of use the same year.

Table 1. The global use of steel in different applications during 2008. Estimates based on Allwood & Cullen (2012).

Steel application	*Total steel quantity (Mt)*	*Steel category*	*Steel quantity (Mt)*
Transport		Sections	32
Cars and Light Trucks	93	Re-Bar	50
		Rolled	11
		Sections	10
Trucks and ships	28	Re-Bar	15
		Rolled	3
Industrial Equipment		Sections	19
Electrical	27	Re-Bar	0
		Rolled	8
		Sections	0
Mechanical	137	Re-Bar	22
		Rolled	115
Construction		Sections	36
Infrastructure	150	Re-Bar	81
		Rolled	33
		Sections	108
Buildings	433	Re-Bar	191
		Rolled	134
Metal Products		Sections	0
Metal Goods	134	Re-Bar	67
		Rolled	67
		Sections	4
Consumer packaging	9	Re-Bar	0
		Rolled	5
		Sections	0
Domestic appliances	29	Re-Bar	0
		Rolled	29
Total	**1040**		**1040**

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 10% per recycling cycle for rolled steel and sections, and 20% for re-bar.

Based on the estimates by Kakudate et al. (2010), we assume that 4 kg of copper is added to each tonne of steel scrap from cars and light trucks, industrial equipment and domestic appliances. This makes the copper content higher in the scrap from these products than in the steel used for producing the products (see Table 2). Already here it can be concluded that steel scrap from machinery etc. is too poor to be directly recycled into new products.

Table 2. The global flows of steel and their copper content in our tentative steady-state model based on Allwood & Cullen (2012) and Kakudate et al. (2010).

	Total steel quantity (Mt)	*Cu in products (%)*	*Scrap quantity (Mt)*	*Cu added in scrapping (kt)*	*Cu in scrap (%)*
Rolled					
Machinery etc.	163	0.10	147	588	0.50
Other applications	243	0.10	219	0	0.10
Sections					
Machinery etc.	51	0.30	45	182	0.70
Other applications	157	0.30	142	0	0.30
Re-Bar					
Machinery etc.	72	0.40	58	231	0.80
Other applications	354	0.40	283	0	0.40

Material pinch analysis

Figure 3 and Figure 4 illustrate how the steel flows in

Table 2 can be plotted in diagrams. Figure 3 presents all applications of steel in a sink composite curve, which describes the total steel-demand. This corresponds to the cold composite curve in Figure 2. Similarly, Figure 4 includes all scrap-supply in a sources composite curve, which corresponds to the hot composite curve in Figure 2.

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 Figure 5). For simplicity we neglect the quality loss in the recycling process (if any) and the minimum safety margin for the quality (if any). 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 Mtonne/year to the right, compared to Figure 3.

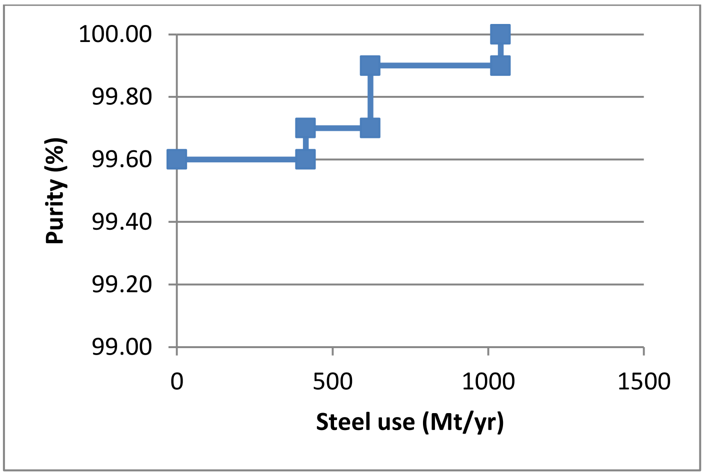

Figure 3. The sink or steel-demand composite curve of the tentative model, based on data from

Table 2. This curve corresponds to the cold composite curve in an energy pinch analysis and to the sink composite curve in the terminology of El-Halwagi et al. (2003). The term purity here refers to the share of non-copper content in the steel.

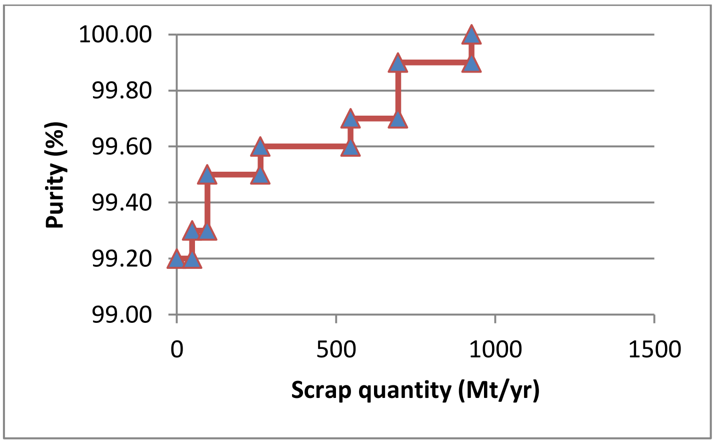

Figure 4. The source or scrap-supply composite curve of the tentative model, based on data from

Table 2. This curve corresponds to the hot composite curve in an energy pinch analysis and to the source composite curve in the terminology of El-Halwagi et al. (2003). The term purity refers to the share of non-copper content in the steel.

Figure 5 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, is 250 Mtonne/year. This is the horizontal distance between the lowest point of the two curves.
- The minimum required quantity of ore-based steel is 397 Mtonne/year. This is the horizontal distance between the tops of the two curves.
- The maximum rate of direct recycling of steel is 62%: (1040-397)/1040 = 0.62.
- The two curves meet at three places. However, the pinch point is at 99.6% purity, because this is the part of the scrap-supply curve that decides how far to the right the steel-demand curve needs to be shifted.

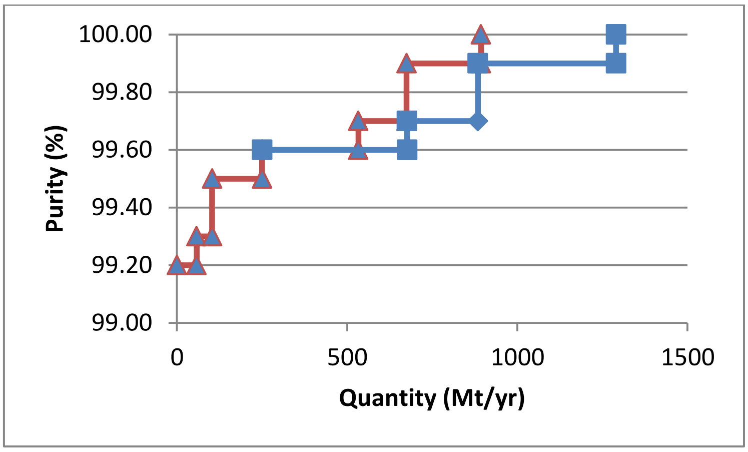

Figure 5. The two composite curves in the same diagram and with the sink composite curve shifted to the right to identify the pinch point.

The pinch rules state that no virgin material should be used for an application below the pinch point (see above). Also, no scrap from a source above the pinch point should be used for an application below the pinch point. These rules do not apply in Figure 5, because there is no steel demand below the pinch point. The only pinch rule that apply is that no scrap from a source above the pinch point should be deposited. This means that all steel scrap from non-machine applications should be recycled.

In practice, annual landfilling of 250 Mtonne of steel scrap is not realistic, because scrap with a high copper content can be 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. (2007). 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 6. With the input data and assumptions above, this excess purity can be calculated to 958 ktonne copper per year:

A1 = 0.001*(676-533) = 0.143 Mtonne/year

A2 = 0.002*(884-675) = 0.418 Mtonne/year

A3 = 0.001*(1290-893) = 0.397 Mtonne/year

A = A1+A2+A3 = 0.958 Mtonne/year = 958 ktonne/year

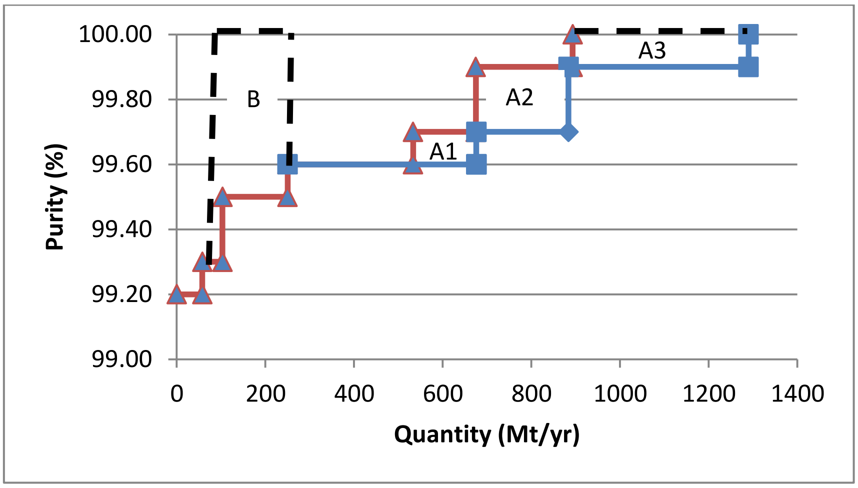

Figure 6. The quantity of copper in poor scrap that can be allowed into the steel recycling (B) is defined by the excess purity in the source (A1+A2+A3). It is 958 ktonne/year.

Area B in Figure 6 also corresponds to 958 ktonne 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 share (70%) 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 71 Mtonne/year. This is the re-bar and 30% of the steel sections from machinery etc.
- The minimum required quantity of ore-based steel is 218 Mtonne/year.
- The maximum rate of recycling of steel is 79%: (1040-218)/1040 = 0.79.

If our tentative model is accurate, the following can be concluded:

1. The maximum rate of direct recycling of steel is 62%; if poor steel scrap is mixed with high-quality scrap and ore-based steel, the maximum recycling rate increases to 79%.

Scrap from old machinery is too contaminated with copper to allow for direct use even in re-bar applications. It needs to be mixed with high-quality scrap or with ore-based steel to facilitate recycling. This is clear already from

2. Table 2.

3. Rebar and 30% of the sections from old machinery etc. should not be recovered for steel recycling. Instead it should be discarded or, possibly, sent to copper recycling.

4. All scrap from applications other than machinery is generated above the pinch point. This means it should all be recycled and none of it should be deposited at landfills.

5. The two composite curves run together for most of the interval with re-bar use and scrap from re-bar in non-machinery applications (99.6% purity). 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 rebar.

Note that a rate of recycling even higher than 79% is possible if less material is lost in the use, collection and recycling of steel, and/or if a more copper is separated from the steel when machinery etc. are dismantled. Improved dismantling can not only increase the maximum recycling of steel but 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.

3.3. Discussion

Our tentative study takes MPA methodology beyond the previous material pinch studies. 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.

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 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. However, some of the conclusions above are likely to be valid already today: steel scrap from non-machinery applications should be recycled, and care should be taken not to use too much ore-based steel and scrap from rolled steel to produce re-bar.

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.

4. To continue

4.1. The idea

In parallel to the tentative case study in the previous chapter, we initiated two applications to make a full case study. A full study would involve several steps, most of which were included already in the tentative study:

1. A measure of the material quality is defined. In the pilot study, we focussed on the copper content as the key impurity in the material. This would probably be adequate also in a full MPA on steel, but not for an MPA of other materials.

2. Quality requirements are defined for different applications of the material. In the pilot study, we distinguished between rolled steel, sections, and re-bar. A full MPA could include further investigations into what is the best typology for applications of the material, and further data sources should be investigated to establish the quality requirements.

3. A material flow analysis is carried through to investigate where the material is used and what the current quality is in different flows of the material. The tentative MPA included adequate data for the use of steel, but a full MPA of the current situation should investigate the actual scrap flows.

4. Recycling and refining processes are investigated to assess the effects of these processes on the quality of the material. This step was not included in our pilot study. Instead we simply assumed that the sink curve has to be at or below the level of the source curve at all places. If the material is refined in the recycling process, for example because a small share of the copper is removed from the steel scrap, the sink curve can be allowed to be slightly above the source curve. If the material is degraded in the recycling process, for example because paper recycling reduces the length of paper fibres, the sink curve has to be a distance below the source curve. If a full MPA includes an analysis of the recycling processes, it might give a basis for quantifying the minimum distance between the composite curves.

5. The MPA is carried through to describe optimum global flows of the material and to quantify the maximum recycling rate, possibly under different assumptions regarding the refining processes etc. All steps in a basic MPA was carried through already in the pilot study. A full MPA could also include an analysis of the potential to increase the maximum recycling rate through mixing different scrap flows and virgin material in new products.

A full MPA would benefit from a network of experts on different fields, for example:

- material quality and quality requirements (Steps 1-2),
- material flow analysis (Step 3),
- recycling processes (Step 4), and
- pinch analysis (Step 5).

If the full study is conducted by a team of researchers from different areas, effective coordination and efficient communication are important to create a common terminology a realistic time plan, etc.

4.2. MISTRA Closing the loop

Mistra issued in 2011 a call for research under the heading Closing the loop – from waste to resource. In response to this call, we initiated an application for a full MPA on steel based on the procedure above (see Figure 7). The tentative budget of this project was 2.6 MSEK.

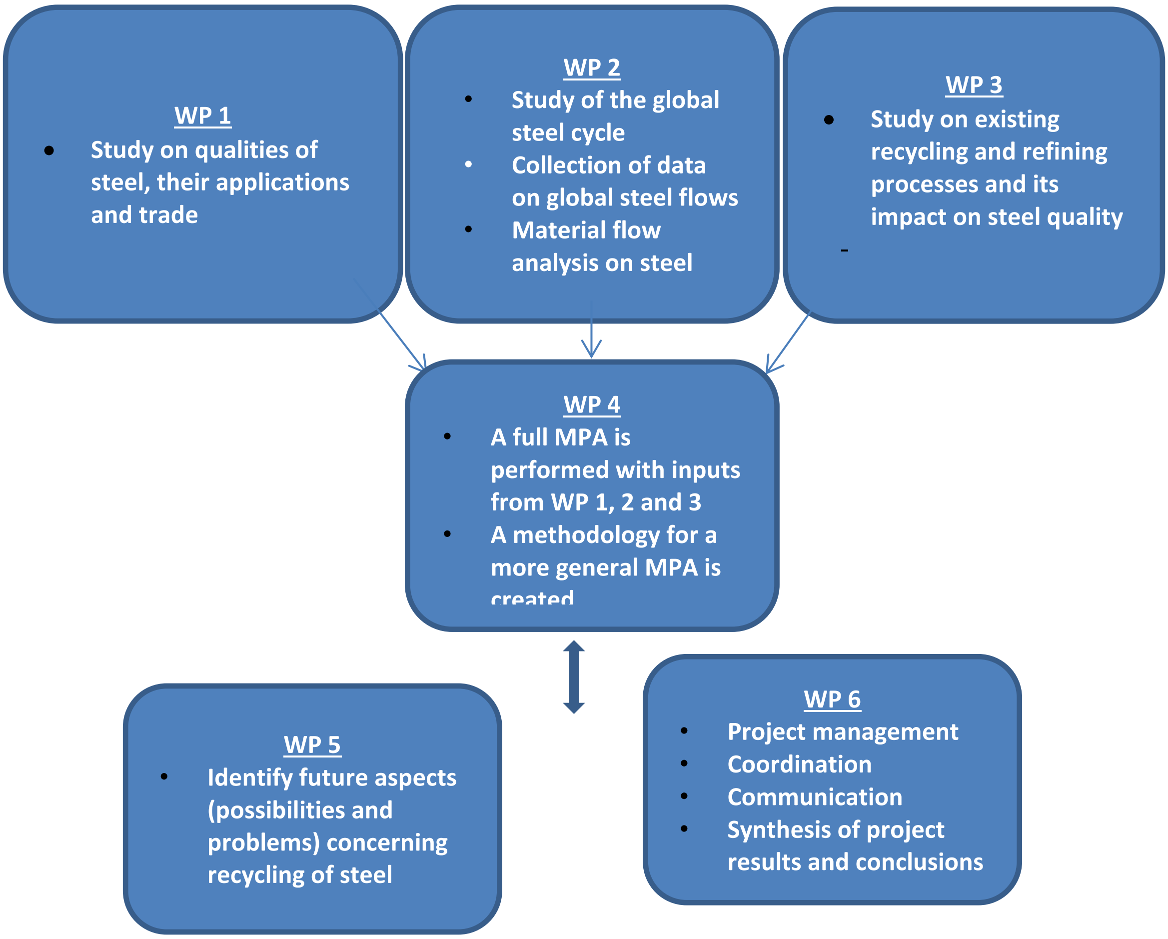

Figure 7: Structure of the application to Mistra Closing the loop.

We contacted researchers at Chalmers University of Technology as well as Royal Institute of Technology to build a team of researchers from the relevant areas. A couple of them were interested to participate in the project or to supervise students making their Master Thesis as part of the project.

We also contacted seven steel and recycling companies to obtain the industrial co-funding required in the Mistra call. Several companies did not find the time to decide on the proposal before it was too late. A couple of companies stated that they did not see a clear value in the project for their company.

In the end the application was not completed, mainly because we did not obtain sufficient co-funding from the industry. This was partly because we initiated the application too late to allow for the necessary decision processes in the companies. However, another reason seems to be that the use of MPA for business purposes is not apparent. The approach is perhaps more relevant to policy-makers and in academic environmental research.

4.3. EU DYNAMIX

In the 2012 call for environmental research within EU Seventh Framework Programme, one of the projects called for was on the development and assessment of European policy for increased resource efficiency. An MPA can be relevant in this context because, in the long run, resource efficiency not only requires management of the quantities of materials but also careful management of the quality of materials.

IVL Swedish Environmental Institute was invited to participate in an application to respond to this call. The application, called DYNAMIX, was coordinated by Ecologic Institute in Berlin, and IVL was given the responsibility for modelling physical flows in the assessment of current and potential future policies. The MPA is one of the tools we have for such policy assessments. Other tools in the toolbox defined for this project includes:

- consequential life cycle assessment,
- material flow analysis,
- water footprinting, and
- dynamic carbon footprinting.

What tools will be used in the end depends on what policies will be assessed and on what aspects of these policies are the most important to assess.

In the evaluation, the DYNAMIX application scored 13.5 out of 15 possible points. Funding was granted. The project started in September 2012 and will run until December 2015. The budget for IVL is 5.7 MSEK. This will be used not only for modelling physical flows but also for development of scenarios, coordinating the generation of ideas for new policies, etc.

5. Conclusions

Our tentative MPA on steel indicates that scrap from old machinery is too contaminated with copper to allow for recycling unless it is mixed with high-quality scrap or with ore-based steel. All scrap from applications other than machinery should be recycled, even in a potential future when steel use does not increase. Ore-based steel need in such a future only be used to displace 1.) material that is lost in the use, collection and recycling system and 2.) scrap from machinery that cannot be mixed with high-quality scrap and be recycled. Care should be taken not to use too much ore-based steel and scrap from rolled steel to produce re-bar.

A full MPA with more thorough data collection would more accurately define the pinch point of the global steel-recycling system. A full MPA would give information on the maximum recycling rate if scrap flows are not mixed. It would probably also give information on the maximum recycling rate when scrap with a high Cu content can be mixed with ore-based material and high-quality scrap. In addition, a full MPA would give information on the minimum quantity of ore-based material, on what applications the ore-based material should be used for and on what scrap flows should be discarded rather than recycled.

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. demonstrates 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.

The results from an MPA can be important for policy-making aiming at increased resource efficiency. The MPA can give information about the significance of improved technologies and systems for recycling. It can also give information on what fractions of different materials should be recycled and where it should be used to allow for maximum resource efficiency

The industrial stakeholders we contacted so far do not clearly see the value of MPA. However, if it is important for policy-making it should also be relevant for industrial companies that can be affected by policies. This can include companies that collect and process waste for recycling, industries with recycling processes, manufacturers that can use recycled materials, and companies that trade in recyclables and recycled materials.

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