An evaluation of alloying elements in shredded steel scrap

Economic and environmental aspects of the recycling process for the steel scrap category E40

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Abstract
The steel manufacturing of today is partly based on steel scrap. In the steel recycling process some elements becomes economically unutilized due to the lack of information about the element content in the steel scrap. The aim of this project is to identify trends and possible improvements in the steel scrap sorting process through increased information about the alloy content within the scrap category E40. In order to do this sub aims are set. The thesis includes literature studies, field visits and calculations based on estimations and found data. The web based software RAWMATMIX® is used in order to execute calculations and collect data. The results conclude that it may be possible to separate alloy enriched scrap and purified scrap. This would result in increased market value of steel scrap, decreased use of virgin material and lower environmental impact.

Keywords: Steel scrap recycling, shredded scrap, scrap flow, ELV, scrap category E40

Sammanfattning

Nyckelord: Stålskrotsåtervinning, Fragmenterat skrot, skrotflöde, ELV, skrotkategori E40
Nomenclature

Degree of sorting: high degree of sorting means that the steel scrap has been separated in different batches depending on alloy content and material properties.

Purified scrap: Steel scrap which alloying content has been reduced during the sorting process due to separation of high alloy steel scrap.

Alloy enriched: Steel scrap which alloying content is increased due to separation of low alloy steel scrap.

Pickable copper: The pure copper parts in the scrap flow which can be seen by the human eye and separated from the bulk scrap flow.

Upstream CO\textsubscript{2}-emission: Emissions that precedes a given life cycle stage.

Tramp element: Undesirable alloying element trapped in the iron matrix.
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1. Introduction

Due to the developing infrastructure and the increase in world wealth, the amount of steel applications and steel products in use has grown. A big challenge is to cater for the increasing need of steel and simultaneously decreasing the environmental impact of the steelmaking process. This is a substantial challenge due to variety of stakeholders with different economic interests and involvements within this field.

In Sweden today, an ample share of steel manufacturing is based on recycled steel scrap. Alloying elements affect both the steelmaking process and the final product; it is therefore beneficial to gain knowledge of the ingoing steel scrap in the recycling process. The steel scrap used in the steelmaking processes of today is sometimes diluted with virgin material due to the lack of information of element composition in the steel scrap.

Steel scrap may contain high levels of alloying elements such as chromium, nickel, manganese and copper. Due to the lack of information of steel scrap composition there is a risk for undesired alloying elements, residuals, in the steel melt.

In order to meet the demands of material properties, alloy elements are added to the steel during the steelmaking process. The importance of a steady access to alloying elements and due to the limited resources of virgin materials it is necessary to utilize the currently used material within the circular material flow.

In order to accomplish improvements regarding the utilization of material and alloying element in the steel scrap, some aspects need to be considered:

- The lack of composition information of today’s recycled steel scrap
- The issues with diverse distribution of elements in steel scrap
- The separation of different valuable alloy enriched steel scrap
- The responsibility gap between those whom the costs of an improved recycling system lays upon

This report will examine some areas in today’s recycling process and identify possible improvements and of the value within steel scrap category E40.

1.1 Aim of the study

The initial aim of this study was to investigate the potential of automatic sorting. Identify trends and possible positive improvements within the steel recycling process. Due to the broad range of the project aim, sub aims are set to proceed with the project:

- Investigate a decreased deviation of tramp element in shredded scrap and the possible effects of a higher certainty.
- Identify valuable metals in shredded scrap to separate and estimate the market value of the alloy enriched steel scrap. Evaluate products within the scrap category E40 that is beneficial for alloy enriched scrap.
- Study how increased producer responsibility could create conditions for improved sorting.
- Create a possible investment model for an automatic sorting system and investigate the profitability from a higher degree of sorting.
1.2 Limitations

This study focuses on the Swedish steel scrap management and the report is limited to the steel scrap category *Shredded scrap*, category E40. Alloying elements identified in this category is nickel, chromium, copper and manganese. These elements are examined due to its great impact on the steelmaking process. The Swedish import and export of steel scrap are not taken into consideration in this report. Possible profits from a higher degree of sorted scrap are examined but this study does not include the technology behind automatic sorting with robots.
2. Background - The handling of Steel scrap

2.1 Alloying elements and their impact in steelmaking processes

In order to improve e.g. the curability or hardness of steel, different alloying elements are added in the steelmaking process. [1]. Common alloying elements in steel are Ni, Cr, Cu and Mn etcetera. Residual or tramp elements is an undesirable alloying element trapped in the iron matrix. All recycled steel has an increased tendency to contain tramp elements since the steel is recycled and re-melted.

Chromium (Cr)

Cr is today seen as the fifth most important metal. Approximately 0.001 % of the earth crust contains Cr. This reserve of unmined ore with a high Cr content is about 2.1 billion tonnes [2]. Cr’s effect on steels is the forming of a passive layer of chromium oxides at the surface which makes the steel more resistant to corrosion. The passive layer is the reason why high levels (above 12%) of Cr in steels are referred to as stainless steel [3]. No chromium deposits have been found in Sweden and the Swedish steel manufacturers are depending on import from exporting countries [2]. Cr is 20 times more expensive than Fe and the CO₂-emissions are 7.5 times higher than for Fe when mining [4].

Nickel (Ni)

Ni is present in the earth’s crust as a compound with oxygen, sulphur, silicon or other elements. It is estimated that the crust contains around 0.002 % Ni [2]. Ni is an important alloying element in steel due to the element’s ability to increase the ductility and the toughness of the steel. Ni is also an austenite stabilizer which makes it a valuable alloying element for austenitic steels [3]. Ni is approximately 30 times more expensive than Fe and the CO₂-emissions when mining for Ni ore is 5 times higher than for Fe [4].

Copper (Cu)

Cu has a large impact on surface defects in steels. When the solubility limit of Cu in the austenite phase is exceeded, a liquid phase is formed and this phenomenon can lead to surface cracking and hot shortness¹. Addition of Ni in steel containing Cu, ratio Ni:Cu; 2:1, prevents the hot shortness. Small additions of Sn have the same influence to decrease problems caused by Cu [5].

Cu is one of the major intrinsic residual impurities and is proven to have an impact on the mechanical properties of the steels, often in an undesired way for the steel manufacturers. Presence of more than 0.25 % in steels usually forms complex compounds that cause unwanted distortions in the microstructure, leading to change in the mechanical properties [6].

Cu may be added in the steelmaking process because of its characteristics and previous studies have shown that precipitates of Cu may improve the poise between strength and ductility. This phenomenon is due to the different characteristics of the precipitates of Cu compared to other precipitates, e.g. nitrides. The studies have also shown that there is a tendency that the precipitates of Cu are finer than, for example, nitrides and therefore achieve finer grain-sizes [7]. Cu is approximately 15 times more expensive than Fe and the CO₂-emissions when mining for Cu ore is 5 times higher than for Fe [4].

Manganese (Mn)

Manganese is an important alloying element in steel alloys. High Mn steels provide an increase in ductility, formability, strain hardening and strength levels. By using high strength steels, it is possible to reduce the amount of steel which will reduce the cost and the environmental impact.

¹ Hot shortness is the tendency of separation of alloy element along the grain boundaries.
Manganese also has an important role when the steel contains sulphur (S), which may contaminate the steel. Mn has the ability to form MnS when S is present. The kinetic of the precipitation of MnS reduces the sulphur content and thereby the hot ductility increases [8, 9]. Mn is approximately 4 times more expensive than Fe and has double the CO₂-emissions when mining compared to Fe [4].

2.2 Phases in steel as a result of alloying elements

Alloying elements in steel affect the structure of the steel and create different phases. Some of the most common phases in steel are the ferritic and the austenitic phases. The ferritic stabilizers include, among others, Cr, and austenite stabilizers include, as earlier mentioned, Ni and also Mn. One important difference of those phases, except different mechanical properties, is the magnetism of the steel. Ferritic steel is magnetic at room temperature due to the atomic structure and austenitic steel is non-magnetic at room temperature [10].

Some alloying elements may create phases in the material and changes the material properties, occasionally in an undesired way. The Fe-Mn system and Fe-Cu system are some of the exceptions that do not create intermetallic phases. The Fe-Cu system creates a wide miscibility gap between the iron rich face centred cubic phase (fcc) and the copper rich fcc-phase. The Fe-Mn system on the other hand shows a full miscibility in the gamma phase. Steels that contain Fe-Cr-Ni system with Mo additions may precipitate sigma-phase under certain conditions. The sigma-phase increases the embrittlement of the steel [1].

2.3 The problems of removing alloying elements from the iron matrix

When scrap steels enter the steel mill and is melted in an Electric arc furnace (EAF) a sufficient analysis of the ingoing material is important. Once the scrap has been melted in the EAF all the alloying elements are dissolved in the iron matrix. Due to the difficulty of removing alloy elements metallurgical, the steel in the EAF process sometimes need to be diluted with virgin material to accomplish the required composition [11].

The Ellingham diagram predicts the temperature dependence of thermodynamically stabile compounds but it does not take the kinetic reactions into account. The diagram is a useful tool to predict the conditions in which the metal undergoes a reaction to an oxide [12]. A metal with high potential to form an oxide has a low Gibbs free energy, i.e. a low position in the Ellingham diagram. Copper, for example, has an upper position in the diagram, as can be seen in Figure 1. Cu is therefore difficult to remove from a steel melt, as Fe becomes an oxide prior to Cu [13]. In the case of an oxidation of an alloying element prior to Fe this alloy element forms an oxide slag at the melt surface, which is removed. If an alloy element forms an oxide slag it becomes unutilized material sources [11].
Figure 1 The Ellingham Diagram as a tool for evaluation in what order elements become oxides dependent of temperature and p(O_2), CO/CO_2- or H_2/H_2O-ratio [14].

2.4 Direct Reduced Iron (DRI)

Direct reduced iron (DRI) is a virgin material created when reducing iron ore from oxygen with a reducing gas and without melting. The reducing gas compound consists mainly of H\textsubscript{2} and CO [15]. DRI can be used as virgin material in the steelmaking process and is added in the electric arc furnace [16]. DRI is sometimes delivered to the steel manufactures as Hot Briquetted Iron (HBI) due to the increase of density. HBI have been compacted at temperatures greater than 650°C [17].

2.5 Shredded scrap (E40)

Swedish metallic scrap is divided into different categories and shredded scrap 117 is one of them. The corresponding category in European standards is category E40. This category of shredded scrap
has requirements on Cu content with a maximum of 0.25% and an upper limit of the Sn content at 0.02%. The Swedish *Skrotboken* regulates the maximum limits of density, moisture and geometry in this category. The E40 category accounts for the majority of major home appliance, vehicles and metallic household scrap that is recycled today [18].

2.6 Recycling process for scrap category E40

Steel are among the most recycled materials. There are two separate metal recycling sectors, the industrial scrap sector and the private consumption sector. The industrial scrap, steel recycled within the steel industry, contains a known material analysis and a small distribution of unknown alloy elements. The private post use consumption scrap has a large distribution of metallic elements with unknown analysis of the composition. Due to the high amount of contaminations in private consumption scrap it is more difficult to handle in the recycling process [19]. In sections below the different recycling process for scrap category E40 steps is described.

Disassembly

Non-reusable parts, like air-conditioner coolants and airbags in vehicles are disassembled, as well as the engine and other reusable parts. The disassembly process is mainly targeted at vehicles but some disassembly occurs in major home appliance due to the risk of leakage of chlorofluorocarbons (CFC). Easily removed parts with high copper content may in some cases be separated from the vehicle before shredding [20].

Shredding

The remaining parts of the vehicle after disassembling are shredded together with metallic household scrap and major home appliances. When shredding, the product is torn into small pieces to reduce the volume of the scrap [20].

Material sorting

When the scrap is shredded ferritic and austenitic steel is separated by applying an electromagnet [20]. Of all metallic scrap collected 10 % is austenitic steel and the remaining 90 % is ferritic steel [21].

Cu is removed from the shredded scrap manually, this is important since Cu is a great contaminant in recycled steel. If the shredded scrap contains a higher amount of Cu than regulations in the scrap category, pure iron must be added later in the steelmaking process in order to dilute [20].

2.7 Products within scrap category E40

The following section includes products and material content in scrap category E40.

Recycling of major home appliance

The manufacturing of major home appliance, such as microwaves, ovens, refrigerators and washers has increased. Major home appliance amounts to about 10 % of the total collected metal scrap associated with the category E40 [21]. Total amount of recycled major home appliance in Sweden year 2015 was 34 460 tonnes [22].

When shredding major home appliances there is a risk of leakage of Chlorofluorocarbons (CFC). Therefore, all major home appliance needs to be depolluted of CFC [23]. Material content in major home appliances is presented in Table 1.
Table 1. Material content of collected major home appliance in the year of 2015. Total amount of recycled major home appliance in Sweden year 2015 was 34460 tonnes. N/A: not available information [22].

<table>
<thead>
<tr>
<th>Material</th>
<th>[kg/tonne scrap]</th>
<th>[%]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fe</td>
<td>690</td>
<td>69</td>
</tr>
<tr>
<td>Cu</td>
<td>5</td>
<td>0.5</td>
</tr>
<tr>
<td>Ni</td>
<td>30</td>
<td>3</td>
</tr>
<tr>
<td>Mn</td>
<td>N/A</td>
<td>N/A</td>
</tr>
<tr>
<td>Cr</td>
<td>N/A</td>
<td>N/A</td>
</tr>
<tr>
<td>Mo</td>
<td>N/A</td>
<td>N/A</td>
</tr>
<tr>
<td>Other Metals</td>
<td>70</td>
<td>7</td>
</tr>
<tr>
<td>Other Materials</td>
<td>205</td>
<td>20.5</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td><strong>1000</strong></td>
<td><strong>100</strong></td>
</tr>
</tbody>
</table>

Recycling of Vehicles

The total number of vehicles in use in Sweden has increased by 500 000 during the period 2007 to 2016, see Figure 2. Statistics over shredded vehicles can be seen in Table 2. The average usage of a vehicle is 10-15 years and 95% of the end-of-life vehicles (ELV) weight is recycled due to the high value in material, the recyclability of metal and due to the extended producer responsibility, see 2.12.

Figure 2. Passenger cars in use in Sweden from year 2007-2016 divided by energy source [24].
Table 2. Shredded vehicles in Sweden from year 2007 to 2016 [24].

<table>
<thead>
<tr>
<th>Year</th>
<th>Number of shredded vehicles in Sweden</th>
</tr>
</thead>
<tbody>
<tr>
<td>2007</td>
<td>213 408</td>
</tr>
<tr>
<td>2008</td>
<td>142 219</td>
</tr>
<tr>
<td>2009</td>
<td>125 538</td>
</tr>
<tr>
<td>2010</td>
<td>160 292</td>
</tr>
<tr>
<td>2011</td>
<td>172 382</td>
</tr>
<tr>
<td>2012</td>
<td>173 565</td>
</tr>
<tr>
<td>2013</td>
<td>177 191</td>
</tr>
<tr>
<td>2014</td>
<td>173 611</td>
</tr>
<tr>
<td>2015</td>
<td>176 175</td>
</tr>
<tr>
<td>2016</td>
<td>173 291</td>
</tr>
</tbody>
</table>

In Sweden, approximately 170 000 vehicles were shredded in the year 2016 [24]. Currently, about 75% of the vehicle's weight is profitable to recycle through the shredding process. Some parts from the vehicle end up in the reuse and remanufacturing industry. The recycling of vehicles stands for the majority of recycled ferritic scrap that is later used in the iron and steel making industry [23].

A vehicle's weight is predominantly metals, in Table 3 materials by car segment is presented. The total material content of all shredded vehicles in 2016 is calculated in the far-right column in Table 3. Vehicles also contain a variety of steels, mostly conventional steel but also high strength steel and stainless steel, the percentage of different steels can be seen in Table 4.

Table 3. Element content in vehicles by segment [25].

<table>
<thead>
<tr>
<th>Element</th>
<th>Car segment</th>
<th>[kg]</th>
<th>[wt-%]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fe</td>
<td>Body</td>
<td>1000</td>
<td>81.4</td>
</tr>
<tr>
<td>Cu</td>
<td>Electric cables, radiators</td>
<td>20</td>
<td>1.6</td>
</tr>
<tr>
<td>Ni</td>
<td>Surface coating, stainless steel</td>
<td>4</td>
<td>0.33</td>
</tr>
<tr>
<td>Mn</td>
<td>Aluminium alloys containing Mn</td>
<td>8</td>
<td>0.66</td>
</tr>
<tr>
<td>Cr</td>
<td>Chrome details</td>
<td>7</td>
<td>0.57</td>
</tr>
<tr>
<td>Mo</td>
<td>Engine lubrication, steel</td>
<td>0.5</td>
<td>0.04</td>
</tr>
<tr>
<td>Other Materials</td>
<td>All other</td>
<td>189</td>
<td>15.4</td>
</tr>
<tr>
<td>Total</td>
<td></td>
<td>1 229</td>
<td>100</td>
</tr>
</tbody>
</table>
Table 4. Metallic content and content of different steels in a vehicle with a total weight of 1375 kg with 73 % metal content and 23% other material [26].

<table>
<thead>
<tr>
<th>Material</th>
<th>[%] of vehicles</th>
</tr>
</thead>
<tbody>
<tr>
<td>Conventional steel</td>
<td>38.4</td>
</tr>
<tr>
<td>High-strength steel</td>
<td>12.1</td>
</tr>
<tr>
<td>Stainless steel</td>
<td>1.7</td>
</tr>
<tr>
<td>Other steel</td>
<td>0.8</td>
</tr>
<tr>
<td>Cast Iron</td>
<td>7.5</td>
</tr>
<tr>
<td>Copper</td>
<td>1.2</td>
</tr>
<tr>
<td>Other metals</td>
<td>1</td>
</tr>
<tr>
<td>Total metals</td>
<td>73</td>
</tr>
</tbody>
</table>

Household scrap

In 2012, the total metallic scrap collected from household and equivalent scrap from business operations in total was approximately 197 000 tonnes [21].

Table 5. Element content in metallic household scrap [27] N/A: not available information.

<table>
<thead>
<tr>
<th>Material</th>
<th>Total element amount from metallic Household scrap [tonne]</th>
<th>[%]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fe</td>
<td>196800</td>
<td>99.9</td>
</tr>
<tr>
<td>Cu</td>
<td>200</td>
<td>0.1</td>
</tr>
<tr>
<td>Cr</td>
<td>N/A</td>
<td>N/A</td>
</tr>
<tr>
<td>Ni</td>
<td>N/A</td>
<td>N/A</td>
</tr>
<tr>
<td>Mn</td>
<td>N/A</td>
<td>N/A</td>
</tr>
<tr>
<td>Mo</td>
<td>N/A</td>
<td>N/A</td>
</tr>
<tr>
<td>Other Metals</td>
<td>N/A</td>
<td>N/A</td>
</tr>
<tr>
<td>Total metal shredded Tonnes/year</td>
<td>197000</td>
<td>100</td>
</tr>
</tbody>
</table>

2.8 Recycling and Sustainability

Recycling of scrap promotes sustainability due to the impact that the steelmaking industry has on the CO₂-emissions. Due to the development of steel products, for example lightweight vehicles, the production now includes materials such as polymers, composites, high- and medium-strength steel and an increase of the usage of magnesium and aluminium. The request and interest for hybrid vehicles is growing and the need of materials like cobalt and nickel. The materials used in hybrid vehicles batteries are expensive and if not recycled a shortage of virgin material will arise [23].

2.9 Grades of recycling

In order to limit the increase of generated scrap, legal framework from the EU is reinforced to control the entire scrap cycle. The highest grade in the recycling hierarchy is preventing scrap and the second highest is the re-usage. Material recycling is the third step in the recycling hierarchy latter [23], see Figure 3.
2.10 The theory of Circular economy

Circular economy means to “close the loop” of product lifecycles by either recycling or re-use. This is of great importance for the environmental and economic impact. The aim is to extract the maximum value and use of raw materials in a consumed product and to limit the CO₂-emissions. The European Commission has invested in a project, which evaluates and makes improvements to the circular economy in EU until year 2020 [23].

The circulation of metallic elements in the society

Since the metallic elements cannot be created nor disappear the materials circulate in society. The broad variation of steel applications makes it difficult to estimate the average life length of a steel
product. The variation also affects the possibility to calculate the recycling rate of steel based products [29].

2.11 Extended Producer Responsibility (EPR)

The objective of the EPR is to reduce the overall environmental impact of a product. In order to achieve this, responsibility to take care of the entire product life cycle is placed on the producer. Some products are very complex and have a long and varied life cycle. This makes the extended producer responsibility for certain products advanced and difficult to identify. Complex products are for example vehicles and the electronics in major home appliance [30].

2.12 Legal requirements regarding recycling

Producer responsibility

End-of-life vehicles (ELV) and Waste of Electrical and Electronic Equipment (WEEE) are two EU directives that include producer responsibility for recycling. The purpose of the directive is to ensure the good management of the recycling of ELV and WEEE. Major home appliance and metallic household scrap are two categories that are covered in the WEEE directive [22]. The EU Directives states that member states should encourage producers to meet the financing of the collection, treatment, recovery and recycling affected by their product [31, 32].

Producer responsibility in Sweden

Between 1975 and 2007 Swedish law stated the possibility to get a deposit from the government when recycling vehicles. This law was formed in order to prevent abandoned vehicles in nature that is environmentally harmful. This was replaced 2007 with the extended producer responsibility. The deposit-system is an effective way to encourage people to submit ELV for recycling in conjunction with implementing such system. Problems with this system are the import of ELV to gain economical profit and lack of increased recycling long-term [33, 34].

Today the producer responsibility is established in Sweden. According to the Swedish law the producers must ensure that there is a recycling system that takes care of used cars. This recycling system should be able to reuse or recycle at least 95 % of the total weight [35].

In line with the EU-directive WEEE there is also producer responsibility for electrical and electronic products in Sweden. Electrical and electronic products include major home appliance and metallic household scrap. By law, the producers are thereby responsible for providing a recycling system for the used product [36].

Requirements for recycling companies

Requirements for recycling companies in Sweden are not controlled by law, but there are directives for responsibility initiated and gathered in Skrotboken. The directives cover restrictions for scrap handling before delivering the scrap to the steel company [18].

Consumer responsibility

According to the Swedish environmental law the consumer has a responsibility for its’ waste. A consumer is not allowed to leave any waste in a public place. This law prevents consumers from not submitting broken or consumed vehicles, major home appliance and metallic household scrap to authorized recycling companies [37].
3. Method

The work presented in this report is based on statistics, collected data, field visits and communications with stakeholders [38, 39, 40, 41]. Field visits included one recycling company (Ragn-sells, Västerås, Sweden) [38], one steelmaking company (OVAKO, Smedjebacken, Sweden) [39] and one of the major recycling stations in Stockholm (Sätra, Sweden) [42]. On these field visits the process capability, process steps and wanted outcomes was investigated.

Calculations presented in this report are partly produced with the software RAWMATMIX®, and its database. Calculations have also been made based on estimations and assumptions established from statistics [21, 22, 24, 43] and collected data presented in section 2. Together with professionals in the field [41] the accuracy of these assumptions has been evaluated. In the result presented in section 4 some of the figures have a reference source and are evaluated on found data. Some results presented in the following section are based on data collected from available sources. Figures which do not have a reference are based on values presented earlier in the report and/or qualified estimations presented in the related section.

3.1 Software RAWMATMIX®

RAWMATMIX® is web based programs which calculates or optimizes scrap steels amounts or ratio in order to get an optimal mix of raw materials for the properties desired for the final steel product. The system takes scrap properties, such as scrap class, and other important parameters into considerations when calculating. Changes in raw material analysis and restrictions of the targeted product can be done. RAWMATMIX® gives access to calculations with several types of products, including construction steel and ferritic or austenitic stainless steel. When calculated or optimized the result, an analysis of the composition in the targeted product can be done. The calculated results also include cost per tonne and total CO₂-emmission. The software uses mathematical algorithms to calculate or optimize the amount of raw input material. The calculation tool is currently used at different steel plants in both Sweden and Norway [44].
4. Results

Calculations on distribution and alloying elements within the steel scarp category E40 are presented in this part of the report. Aspects evaluated are changes in market price and the environmental impact of recycled steel. All calculations include a significant number of assumptions and estimations since the information in this field is limited. In calculations with RAWMATMIX®, version 2.11, a combination of data from the literature study and the software database has been used.

Since the scrap category E40 has limitations for Cu and Sn content, a general analysis from the scrap category is taken from RAWMATMIX® database. This analysis is used to estimate content of other alloy elements.

Calculations and results presented in this report only investigate the ferritic flow. The spread of the ferritic flow is calculated in the material substance analysis.

4.1 Substance flow analysis

This section contains an analysis of material substance flow in the recycling processes of today. Element content is estimated from field visits, literature studies and discussions with professionals in this field.

Assumptions in calculation for material substance flow

Calculations of the volume in the non-Ferritic flow are based on the following assumptions.
- A high Ni flow would contain 6% Ni based on non-ferritic stainless steel products. Added to this Ni enriched flow, 10% of the total ingoing pure Cr scrap is estimated to follow this non-ferritic flow.
- A high Mn flow would contain 1-2% Mn.
- The remaining fraction of both the high Ni and the high Mn flow is estimated to be pure iron.
- All Cu is coupled with a Fe unit and therefore no Cu is found in the non-ferritic flow.
- Visible copper is removed from the ferritic flow to meet the requirements of maximum 0.25% Cu in the category, E40. This pickable copper is estimated to be pure copper with an insignificant content of other metals.

Substance flow of ELV

Input material content in Figure 5 is calculated with the limitation that all vehicles recycled has the same metal content as presented previously in this report, see Table 3. Some parts are removed from the vehicle before shredding but due to the lack of information about to which extent this is done this has not been taken into consideration when calculating the substance flow. The non-ferritic flow is estimated to 10% of a total of 77% ingoing shredded scrap and 15% of the flow is estimated to be shredding residue containing plastic, foam and other non-metallic materials [45]. The non-ferritic flow is assumed to only contain 50/50 high Ni and high Mn [41].
Substance flow of major home appliances

Input material in Figure 6 is calculated based on the limitations that all major home appliances has the same material content as presented in Table 1. No regard to different products within the sector has been considered. There has been no consideration of metal loss in the disassembling process. The non-ferritic flow is estimated to 10% of total ingoing shredded scrap and is assumed to only contain 50/50 high Ni and high Mn. Due to the lack of information regarding Cr and Mn content this has not been taken into account when calculating the ferritic flows metal content. 15% of the flow is estimated to be shredding residue containing plastic and other non-metallic materials.

Substance flow of metallic household scrap

Input material in Figure 7 is calculated from data presented in Table 5, 100% of the metallic household scrap is shredded together as E40 scrap is based on estimations from field visits. This is established on the diminutive fraction of e.g. high strength steel or stainless steel that belongs to another metallic scrap category. Due to the low content of Cu no regard to sorting has been done.
4.2 Purified Scrap

In the following section of the report the distribution of alloy content in higher degree of sorted scrap is investigated. The relationship between manufacturing steel from alloy enriched scrap compared to manufacturing steel with purified scrap is evaluated.

Distribution of alloying elements in purified scrap

In Figure 8, Figure 9 and Figure 10 the distribution of alloying elements, Cu, Cr and Ni is presented. Alloving content is analyzed from 88 samples taken from a purified shredded steel scrap at a recycling company in Stockholm, Sweden [43]. The purified scrap has been manually sorted from high alloy steel and pickable copper removed before analyzing. Figure 8 shows the Cu content; two samples exceed the restriction of 0.25 % Cu for scrap category E40. In Figure 9 Ni content is presented. Of the 88 samples taken, 64 samples contained approximately 0 % Ni. Cr content in the analyzed scrap is shown in Figure 10.
Figure 8 Quantity of total 88 samples taken containing Cu taken from purified scrap [43].

Figure 9 Quantity of total 88 samples taken containing Ni taken from purified scrap [43].
Virgin material and Scrap relationship in steelmaking

Calculations comparing the theoretical different degrees of purification of shredded scrap are evaluated based on analysis from purified scrap [43]. An optimized ratio between shredded steel scrap with known analysis and virgin material such as DRI or HBI in the steelmaking process is identified. Decrease in product price, CO₂ emission and minimized share of virgin material is targeted in the optimization. The calculations executed a theoretical test melt with the same targeted final analysis in all the cases. In Table 7 the targeted final analysis, low alloy high strength steel, is presented.

Estimations of different degrees of sorting are summarized in .

Table 6 and based on the following:
- Case A: Today's sorting, based on data from RAWMATMIX®.
- Case B: Low sorted steel scrap, decrease in amount of alloying elements based on case 1.
- Case C: Medium sorted steel scrap, decrease in alloying elements based on case 1 and 2.
- Case D: Purified steel scrap, based on previous analysis of purified scrap [43].

<table>
<thead>
<tr>
<th>Alloying element</th>
<th>Case A (shredded)</th>
<th>Case B (low sorted)</th>
<th>Case C (medium sorted)</th>
<th>Case D (high sorted)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cu</td>
<td>0.25</td>
<td>0.20</td>
<td>0.10</td>
<td>0.057</td>
</tr>
<tr>
<td>Ni</td>
<td>0.10</td>
<td>0.08</td>
<td>0.03</td>
<td>0.009</td>
</tr>
<tr>
<td>Mn</td>
<td>0.80</td>
<td>0.70</td>
<td>0.50</td>
<td>0.337</td>
</tr>
<tr>
<td>Cr</td>
<td>0.20</td>
<td>0.17</td>
<td>0.10</td>
<td>0.032</td>
</tr>
<tr>
<td>Mo</td>
<td>0.01</td>
<td>0.017</td>
<td>0.017</td>
<td>0.017</td>
</tr>
</tbody>
</table>

Figure 10. Quantity of total 88 samples taken containing Cr taken from purified scrap [43].
Table 7. Targeted product when calculating the following results. Based on a low alloy high strength steel from a Swedish steel manufacturer. Targeted analysis in alloy element Cu, Ni, Cr, Mo is set to “0” due to the minimized wanted alloy content in target product. The upper limit for element content is presented due to the fact that all products within this interval are accepted.

<table>
<thead>
<tr>
<th>Element</th>
<th>Targeted analysis [%]</th>
<th>Upper limit [%]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fe*</td>
<td>*</td>
<td>*</td>
</tr>
<tr>
<td>Cu</td>
<td>“0”</td>
<td>0.1</td>
</tr>
<tr>
<td>Ni</td>
<td>“0”</td>
<td>0.1</td>
</tr>
<tr>
<td>Mn</td>
<td>0.2</td>
<td>0.4</td>
</tr>
<tr>
<td>Cr</td>
<td>“0”</td>
<td>0.1</td>
</tr>
<tr>
<td>Mo</td>
<td>“0”</td>
<td>0.03</td>
</tr>
</tbody>
</table>

*target composition is balanced with Fe

Results from target product calculation are presented in Figure 11 and Figure 12. Different input material is according to Table 6. Figure 12 compares the total CO₂-emissions in different cases A-D. The CO₂-emissions data covers both upstream and production process emissions.

Figure 11. Estimated ratio of HBI/DRI compared with different cases of scrap with different degrees of sorting, see Table 6. Targeted product is low alloy high strength steel. Y-axis shows the added amount of the different materials in the steelmaking process. Calculated with RAWMATMIX®.
4.3 Alloy enriched scrap

This section of the report shows the possible market value of a scrap with a higher degree of sorting according to alloy content than today - alloy enriched scrap.

Comparison of market price for E40 scrap and DRI

Price data for E40 have been collected from the German market and price data for iron ore pellets have been collected from the Chinese market. RAWMATMIX® is used to determine the price relation between DRI and iron ore pellets, see Equation 1 and used data below. The result is presented in Figure 13.
- DRI: 290 USD/tonne
- Iron ore pellets: 163 USD/tonne
- DRI/Iron ore pellets – relation: 1.779

This is valid during the circumstances that the change in DRI price follows iron ore pellets price.

\[
\frac{Y_{DRI\ price}}{X_{\text{Iron ore price}}} = 1.779 \quad \rightarrow \quad Y_{DRI\ price} = X_{\text{Iron ore price}} \times 1.779
\]

Figure 12. Total CO\textsubscript{2}-emissions (upstream and processes) from the different cases A-D presented in Table 6 when calculating the theoretical ratio of virgin material/scrap in the steelmaking process. Targeted product is a low alloy high strength steel. Calculated with RAWMATMIX®.
Figure 13. Market price for Shredded scrap (E40) and DRI is presented. Data for E40 is taken from the Swedish ironworks supplies (JBF) and iron ore pellets from the Swedish geological investigations (SGU).³

Possible market value of an alloy enriched scrap

Based on RAWMATMIX® the price for E40 is set to 255 USD/tonne. Price relation between Fe and the alloying components Cu, Ni, Cr and Mn is presented in Table 8. Due to RAWMATMIX® data on Fe content of 98% in E40 the Fe price is set to the price of E40.

Assumption regarding alloy content in possible alloy enriched scrap batches:
- High Cu scrap in the ferritic flow is estimated to contain 10 - 60% pure Cu attached to a ferritic iron unit. Scrap units with higher Cu content will end up in the non-ferritic flow due to Cu nonmagnetic properties, see chapter 4.1
- High Cr steel scrap is estimated to have a lower limit of 4% Cr and an upper limit of 10 % Cr in the scrap category.
- High Ni steel scrap is estimated to have a lower limit of 1% Ni and an upper limit of 3% Ni in the scrap category.
- High Mn steel scrap is estimated to have a lower limit of 1% Mn an upper limit of 1.5% Mn I this scrap category.

Presented in
Table 9, the upper and lower limit of alloy content is divided into three cases. Case 2 in Table 9 consists of the mean value in alloy composition. The different alloy enriched scrap batches are balanced with Fe.

³ Data is undisclosed
Table 8. Price relation, and values, of different alloying elements compared to Fe, based on [4].

<table>
<thead>
<tr>
<th>Element</th>
<th>Price relation</th>
<th>USD/tonne</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fe/E40</td>
<td>1</td>
<td>255</td>
</tr>
<tr>
<td>Cr</td>
<td>20</td>
<td>5100</td>
</tr>
<tr>
<td>Ni</td>
<td>30</td>
<td>7650</td>
</tr>
<tr>
<td>Cu</td>
<td>15</td>
<td>3825</td>
</tr>
<tr>
<td>Mn</td>
<td>4</td>
<td>1020</td>
</tr>
</tbody>
</table>

Table 9. Upper limit, mean value and lower limit of estimated alloy content is presented in three cases.

<table>
<thead>
<tr>
<th>Case 1 – lower limit</th>
<th>Case 2 – mean value</th>
<th>Case 3 – upper limit</th>
</tr>
</thead>
<tbody>
<tr>
<td>High Cr steel</td>
<td>4% Cr</td>
<td>7% Cr</td>
</tr>
<tr>
<td>High Ni steel</td>
<td>1% Ni</td>
<td>2% Ni</td>
</tr>
<tr>
<td>High Cu scrap</td>
<td>10% Cu</td>
<td>35% Cu</td>
</tr>
<tr>
<td>High Mn steel</td>
<td>1% Mn</td>
<td>1,25% Mn</td>
</tr>
</tbody>
</table>

The price of the different high alloy scrap batches has been calculated by the price of the pure metal and the metal fraction in the three cases, as can be seen in Equation 2.

\[
Y_{Price \text{ high sorted scrap}} = X_{Price \text{ alloy}} \times Z_{Fraction \text{ alloy}} + X_{Price \text{ Fe/E40}} \times Z_{Fraction \text{ Fe/E40}}
\]

\[
X_{Price \text{ E40}} = 255 \frac{USD}{tonne}, \text{ data from Table 8}
\]

Table 10. Calculated price for high alloy scrap batches case 1, case 2 and case 3 based on Equation 2.

<table>
<thead>
<tr>
<th></th>
<th>Case 1 – lower limit</th>
<th>Case 2 – mean value</th>
<th>Case 3 – upper limit</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fe/E40</td>
<td>255</td>
<td>255</td>
<td>255</td>
</tr>
<tr>
<td>High Cr steel</td>
<td>449</td>
<td>594</td>
<td>740</td>
</tr>
<tr>
<td>High Ni steel</td>
<td>329</td>
<td>403</td>
<td>477</td>
</tr>
<tr>
<td>High Cu scrap</td>
<td>3111</td>
<td>3468</td>
<td>3825</td>
</tr>
<tr>
<td>High Mn steel</td>
<td>263</td>
<td>2645</td>
<td>267</td>
</tr>
</tbody>
</table>

In order to compare the market value of 1 tonne of E40 with 1 tonne alloy enriched scrap, possible percentage of alloy enriched scrap batches is estimated. Table 11 summarizes possible outcome for different alloy enriched scrap based on material substance flow, see Figure 5, Figure 6 and Figure 7. ELV flow separated from the total flow has a higher possible percentage of alloy enriched scrap compared to total flow, see Table 11.
Table 11. Possible percentage of alloy enriched scrap batches.

<table>
<thead>
<tr>
<th></th>
<th>Total flow</th>
<th>ELV flow</th>
</tr>
</thead>
<tbody>
<tr>
<td>E40</td>
<td>98,37%</td>
<td>96,90%</td>
</tr>
<tr>
<td>High Cr</td>
<td>0,28%</td>
<td>0,60%</td>
</tr>
<tr>
<td>High Ni</td>
<td>0,09%</td>
<td>0,005%</td>
</tr>
<tr>
<td>High Cu</td>
<td>0,96%</td>
<td>1,80%</td>
</tr>
<tr>
<td>High Mn</td>
<td>0,30%</td>
<td>0,70%</td>
</tr>
</tbody>
</table>

Figure 14 and Figure 15 presents the possible increase in value when separating Cr, Cu, Mn and Ni creating alloy enriched steel scrap compared to E40 scrap. The figure is a result of Table 10 and Table 11 combined. Figure 14 shows the possible market value from total steel scrap flow of metallic household scrap, vehicles and major home appliance. Figure 15 presents the possible market value from the contribution of vehicle scrap.

![Figure 14. Possible increase in market value when separating alloy enriched scrap from the scrap flow. The total scrap flow is calculated. Note that the y-axis starts at 240 USD.](image-url)
Figure 15. Possible increase in market value when separating alloy enriched scrap from the scrap flow. Vehicle scrap flow is calculated. Note that the y-axis starts at 240 USD.

4.4 Utilization of alloying elements in shredded scrap

In the recycling process today some metals become unutilized. This section of the report shows the fraction between different metals in the scrap category E40 and the amount of unutilized metals. From estimations regarding the material flow in Figure 5, Figure 6 and Figure 7 and the data in Table 1, Table 3 and Table 5, the total metal content in category E40 each year can be calculated. In these calculations export and import have not been taking into consideration. In Figure 16, the alloy content in scrap category E40 from the different product sectors ELV, major home appliance and household waste is presented. In Figure 17, only the alloying elements Cu, Cr, Ni, Mo and Mn within the products are presented.
From the material flow results presented in section 4.1, calculations regarding the utilization of materials can be made. The assumption that Cu is sorted to reach the requirements for E40, which has a maximum on 0.25% Cu, some Cu is assumed to be unutilized. The lack of utilization of elements in the steel scrap category E40 also applies to the alloying elements Cr, Ni, Mn and Mo. Presented in Figure 18 is the amount of unutilized alloying elements divided by total ingoing ferritic scrap and the contribution from ELV.
4.5 The effect the uncertainty in Cu content has on the use of shredded scrap

In the following section the impact of the uncertainty in Cu content due to the scrap analysis has on the steel making process is investigated. With a decreasing uncertainty of the analysis it is possible to increase the share of shredded scrap steel in the manufacturing of steel according to the results presented below. In Figure 19 and Figure 20 the uncertainty of scrap content when entering the steel mills is plotted against the increasing possible use of shredded scrap in the steel making process.

Theoretical calculation of uncertainty

The tolerance interval for analysis, the uncertainty accepted, is calculated with Equation 3 with input $x=0.062$, $a=30$: this data is collected from a purified scrap [43] and the usage of E40 presented in Figure 11. The tolerance, with these input values, is $y=0.02$. The tolerance is then held constant with a change in uncertainty of the analysis in the shredded scrap ($x$). The uncertainty changed from 0.11 to 0.001 [%].

Figure 19 is calculated from the following equation:

$$a = \frac{y \times 100}{x}$$

- $a$ = Possibility of percentage uses of shredded scrap in a steel melt
- $x$ = Uncertainty of the analysis in the shredded scrap
- $y$ = Tolerance interval for the targeted products analysis (held constant in the calculations).
When the uncertainty of Cu content decreases the possible use of shredded scrap (E40) within the steelmaking process increases, see Figure 19.

![Figure 19](image)

*Figure 19. Calculation of varying uncertainty and the possible use of shredded scrap in steelmaking processes.*

Uncertainty of analysis calculated with RAWMATMIX®

Target product was set to low alloy high strength steel, see Table 7. Limitations for accepted material in the steelmaking process are set to shredded scrap, E40, and HBI/DRI. In calculations, the tramp elements for Cu in E40 decreased from $2\sigma=0.083$ to $2\sigma=0.2\sigma$. $2\sigma$ represents the interval for accepted tramp element e.g. if $2\sigma$ is set to 0.083, fraction for accepted tramp elements are targeted to Cu content $\pm0.083$. While tramp element for Cu decreased in E40 the usage of HBI/DRI decreased. The possible use of shredded scrap, E40, in the steelmaking process, increases when uncertainty of Cu content decreases, see Figure 20. When calculating with $2\sigma$ in RAWMATMIX® almost 98 % of the charges in the steelmaking process will fulfil the requirements for the final product’s analysis, i.e. 2 % of the charges will fail to meet targeted analysis.

![Figure 20](image)

*Figure 20. Ratio of shredded scrap compared to virgin material DRI/HBI. Tramp element: Cu. Targeted product: Low alloy high strength steel, see Table 7. Numbers are calculated with RAWMATMIX®. Note that the y-axis has $2\sigma$ and x-axis starts at 25%.*
5. Discussion

The majority of the results presented in this report are based on estimations and therefore it would be a higher level of accuracy if there was an increase of information about the analysis in alloy content within the steel scrap. This would be beneficial for the whole steel scrap system, including recycling companies and the steelmaking industry. An improved information flow could include an analysis of the steel scrap in each step of the recycling process. Recycling process steps where information is needed is for example when the steel scrap is collected and divided into different scrap categories, and when the scrap is shredded and sold to the steel manufacturer. The improved information flow regarding the alloy content would make it possible for the steel manufacturer to decrease the uncertainty of alloy content within the recycled steel. This decrease in uncertainty would increase the possible use of steel scrap for the steel manufacturer. As can be seen in Figure 19 and Figure 20 a decrease in uncertainty of Cu content can increase the use of steel scrap. The alloy content of Cu is important to look at as this alloy has a big impact on the surface defects but also due to the fact that Cu is hard to remove metallurgically in the steelmaking process. An effect of the increased use of steel scrap would be a decrease in the need to use virgin materials in the steelmaking process. One of the problems for the steel manufactures is this unknown analysis in alloy content which forces them to dilute with virgin material or add alloy content in order to make sure the targeted analysis is achieved. The information flow between the recycling companies and the steelmaking companies would decrease the uncertainty and affect the use of recycled steel. The information flow between steelmaking companies and producers is necessary in order to increase the possibility that this information is delivered to the recycling companies. Information of the alloy content within the product could also have benefits like a more correct placement of the product when the consumer brings it to the recycling station. In Figure 21 an illustration of the information flow is presented. This figure shows the directions where an increased information flow could be beneficial.

![Diagram](image)

*Figure 21. A visualization of improved information flow between the stakeholders in the recycling system, delegation possibilities for the government and the circular material flow.*

Figure 21 also shows the ultimate delegation of recycling responsibility. As can been seen in this figure the government’s role is to delegate recycling responsibility between producers and consumers. The Swedish government endorses a circular material flow and if stricter regulations are enforced an improved recycling system could be possible. A current problem with the Swedish law regulation regarding recycling, see section 2.12, is the fact that it only has requirements on the products weight.
According to the Swedish government a percentage of 95% of the products weight should be recycled. This regulation does not ensure that all materials within the product complete its life cycle or is utilized in the recycling process. Sweden’s present recycling regulations also considers the product to be recycled when the product is shredded. There is no further control regarding the utilization of the materials entering the ferritic or non-ferritic flow, see Figure 5 to Figure 7 showing an estimated substance flow. Improvements in Swedish law that could be done are to introduce regulations on percentage of the material within the product that has to be recycled. If the producers’ responsibility included the material within the product a producer would be responsible for ensuring that for example 80 % of all Cu within their product is recycled. This would force the recycling companies to improve the sorting of the scrap they collect. This could also put requirements on the dismantling process of today. If for example 80 % of all the Cu within a vehicle has to be recycled it would be beneficial to separate electronics or other components within the vehicle that contains Cu. The purpose to separate these parts before shredding is due to the concentration of alloy content within different segments in the vehicle, see Table 3. Other regulation that could improve the recycling system is requirements of the reuse of specific parts in products that has a high tendency to be reusable. A motive for the Swedish government to introduce more detailed recycling restrictions is to decrease the CO₂-emissions from mining and the need of virgin materials in the steelmaking process.

In order to decrease the use of DRI or other virgin materials in the steelmaking process it is necessary to ensure that the quality of recycled metal is comparable to the virgin materials. The deviation in alloy content forces the steel manufacturers to have a safety margin whenever they use steel scrap in the steelmaking process. As shown in Figure 19 and Figure 20 a decrease in uncertainty of the analysis would lead to a higher possible use of shredded scrap in the steelmaking process. If a more known analysis in alloy content is available to the steelmaking company it would allow them to optimize and maximize the usage of recycled steel in the process. With a known analysis it is also more cost effective for the steel manufacturers due to fewer targeted analysis fails in the production. A subsequent effect of reducing the use of virgin material is the positive environmental impact. This environmental impact could be representative to the decrease in CO₂ emission when increasing the use of shredded scrap, see Figure 12. Since the steel scrap category E40 has a big volume in Sweden, see Table 1, Table 3 and Table 5, the benefit of increasing the certainty of alloying content and thereby increase the use of steel scrap in the steelmaking process, this would have a great positive environmental impact.

One way to increase the possible use of steel scrap within the steelmaking process is to decrease the uncertainty of alloying content. This can be done by analyzing the alloy content within the recycled steel. Another way to maximize the use of steel scrap is have a higher degree of sorting within the recycling system. Figure 11 shows the possible ratio between the usages of virgin material versus sorted scrap for a low alloy high strength steel product. The figure clearly shows that an increased degree of sorting of the steel scrap, as the different cases A-D describes in Table 6, will decrease the need of diluting with pure, virgin iron in order to hit the targeted analysis. As can be seen in Figure 11 there is a big drop in the need for virgin material between case B and case C. In case D there is no need for virgin material at all when producing the same product. The analysis in case D, see Table 6, is based on an analysis of a well sorted steel scrap. This scrap has been carefully sorted from all potential high alloy scrap pieces making the scrap purified. Due the fact that case D is based on a real analysis makes it clear that it is possible to come down to these levels of alloy content within the steel scrap. If the degree of sorting would increase this could have the effect that the steelmaking companies wouldn’t have to dilute with or use virgin material.

When decreasing the need for virgin material, the environmental impact decrease due to less mining, see Figure 12. When analyzing the CO₂-emission it should be taken into consideration that there are many different parameters that effects the calculations. These parameters can be, for example, electricity use, type of furnace when melting and all other aspects regarding energy use within the production. This is data taken for the total, both upstream and process impact, CO₂-footprint using the software RAWMATMIX®. As can be seen in Figure 12 the CO₂-emissions decrease radically when the need for virgin material decreases. If a comparison between case A and B is done it can be
concluded that when increasing the use of steel scrap by 10% the CO$_2$-emission decreases by 5%. It can also be evaluated that if the steelmaking process need for virgin material is less than 10% (in case C and D) the CO$_2$-emission would decrease by approximately 70%, see Figure 12, compared to case A. If more steel scrap is used in the steelmaking process it is also possible to decrease the volume of each batch due to the higher level of Fe in the steel scrap than in the DRI. This means that if steel manufacturers are using more recycled steel the amount of material needed in the steelmaking process can decrease. If the amount of needed material in the process decreases the raw material expenses may decrease as well. When comparing the iron ore price and the price for scrap category E40 over the last years a correlation can be seen, see Figure 13. It can be established that the DRI price follows the E40 price or vice versa.

If a higher degree of sorting is introduced in the recycling system a purified steel scrap, with high Fe content, can be accomplished. The market value for the purified scrap would possibly be even higher than the market value for E40 today due to its high levels of Fe and less uncertainty of alloying content. If a high degree of sorting is done there would be some alloy enriched metal flow within the recycling process. This different alloy enriched scrap batches could be traded as scrap with high amounts of alloys like Ni, Cr or Cu. As can be seen in Figure 14 the profit from these alloy enriched scrap batches has a significant increase on economic value compared to E40. The market value for an alloy enriched scrap could have an upper limit of 8% compared to today’s revenue of E40. If only ELVs is shredded and recycled separately and a high degree of sorting is accomplished the upper limit for marker value is as high as 16%, see Figure 15. The higher possible market value of alloy enriched scrap from ELVs is due to the product’s high levels of alloying content, see Figure 17. Facts that should be taken into consideration are that some of the Cu in Figure 14 and Figure 15 is manually picked and sold as Cu scrap in today’s recycling process. This means that some of the presented profit in figure 14-15 is today a utilized profit. The results of increased market value of the steel scrap presented in Figure 14 and Figure 15 could be an incentive for the recycling companies to introduce technology that could increase the degree of sorting. This technology could be a combination of sensor technology and robotic technology. The investment for such technology is not evaluated in this report, but it is clear that there is a possible increase in revenue when separating alloy enriched scrap. When comparing the market value for alloy enriched scrap in Figure 14 and Figure 15 it can be seen that the upper limit of market value doubles, from 8% to 16% of the market value for E40. This result could support the need for separating products within the scrap category. In this case if might be more profitable to recycle ELV separately and thereby increase in volume for the alloy enriched scrap.

The scrap analysis in Figure 8 to Figure 10 is carefully sorted manually, separating all scrap pieces that could contain high alloy content. This alloy analysis may function as a criterion for a possible purified scrap. The difficulty to identify alloy enriched scrap for the naked eye makes this sorting more suitable using sensor technology. By using sensor technology that screens the scrap, and gives an analysis of its alloy content, together with an automatic robotic arm that separates the high alloy scrap into different sub flows can be achieved. The remaining scrap should be purified with a high content of Fe. Due to the limitations in this report of not taking the export and import into consideration it is possible that some of the results may not match reality. The material substance flow is probably more complex in reality than presented in this study.

From the result presented in this report it can be seen that the unutilized material value in different products is considerable, see Figure 17. If the recycling process would utilize more of the input metals and sort them it could simultaneously increase the profit and the use of recycled steel due to the purification of the bulk flow, the ferritic flow. This sorting could be done with sensor technology combined with robotic technology. Due to the difficulty to identify alloy elements within the shredded scrap, an automatic sorting system would decrease the uncertainty of alloy content.

During the work on this report some of the aims were not fulfilled. The sub aim to create a possible investment model for robot technology was not investigated due to the lack of time and information in the area. In order to investigate whether an automatic robot solution is profitable an investment model is necessary.
5.1 Ethical, Society and Sustainable perspectives

Due to the likely increase of steel application use in the world it is necessary to have a sufficient recycling process. Due to the environmental impact from mining virgin ore it is more environmentally desirable to utilize the material already in circulation. When establishing a sustainable steel manufacturing process the recycled steel scrap is an important factor. Steel scrap should be seen as a valuable resource in the circular economy.
6. Conclusions

Conclusions drawn from this work are the following:

- In order to have a better recycling process it is necessary to have an extended Information flow of the ingoing materials, so that all stakeholders have improved opportunities to utilize the material.

- Two possible incitements to ensure an improved sorting may be either economical profit or a law regarding extended utilization of raw material.

From the results presented in this study some conclusions can be made regarding the project aims set in the initial phase of the project.

- It is possible to have a higher degree of sorting than today regarding alloy distribution. With a decreased deviation of tramp element it should be possible to increase the use of shredded steel scrap in the steelmaking process.

- During the circumstances presented in this report it is economically beneficial to have a separation between an alloyed enriched scrap and a purified scrap for the steel scrap category E40. Since these products, within scrap category E40, contain valuable elements such as Cu, Cr, Ni and Mn that can be utilized.

- An investment model for an automatic sorting system has not been evaluated in this report. The economic profits from separation between alloy enriched scrap and purified scrap could cover some of the expenses for the investment in automatic sorting technology.

- Different products within the scrap category E40 may be more or less beneficial to separate as alloy enriched steel scrap. Vehicles may be separated from the other scrap in order to produce an alloy enriched scrap flow while household waste may be utilized as purified scrap due to lower alloying content.
7. Future Work

Due to the complexity of the recycling process a lot of further work can be done. The lack of data when calculating the substance flow of scrap in the recycling process indicates that further investigation in this field is necessary. If more data and more exact analysis regarding alloy content in steel scrap would be available, a better estimation of substance flow and a more exact profitability model could be evaluated. In order to get more data, more random sampling of the scrap flow in the recycling process has to be performed.

From this report some conclusions about a possible profit from a higher degree of sorting of the scrap can be drawn. To make the higher degree of sorting doable in the scrap flow, more research about a possible automatic sorting solution has to be done. To implement such a function, in an already working process, one incitement is an economical gain from the automatic sorting. This indicates that a possible investment model should be developed for this sorting process.
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