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Assessing the Environmental Impact of Steel and the presence of Critical Raw Materials: an Improved Tool for Industry

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Abstract

The communication presents an improved simulation tool aimed at assessing the environmental impact of steel grades, and their use of Critical Raw materials, focusing on their composition. Based on the modelling of the Life Cycle Inventory of steel, it simplifies the process by requiring only material composition data as input. Generally, the use of generic databases such as Ecoinvent, make approximations as to the composition of metal alloys, which makes it difficult to make fully informed decisions regarding the sustainability of the material, because the alloying elements have a significant influence on the total environmental impact of the material. Thus, allowing a more accurate quantification of the content of Critical Raw Materials, which, is not currently a regulatory requirement, but is considered a best practice for a more efficient management of available resources, as the European Commission aims at reducing the amount of Critical Raw Materials consumed, and therefore, reducing the imports needed from out of the European Union. To expand its applicability in industries, this improved tool has been developed to allow the introduction of exact compositions obtained through experimental measurements of the actual material consumed in the production process. To demonstrate its practical usefulness, measurements were made on several samples of the steel components using a composition analyser using spectrometry. This is a significant step towards a more accurate and detailed assessment of the environmental impact of materials, providing practical tools for sustainable resource management in the industry, as it allows to easily quantify the total amount of Critical Raw Materials consumed by a factory, while also assessing the environmental impact of the consumed raw materials.

Keywords: Life Cycle Assessment; Simulation tool; Critical Raw Material; Environmental Impact; Steel

1. Introduction

1.1. Material selection from a sustainable approach

Concern for environmental issues is increasingly relevant today, generating urgency in the scientific and business community to find sustainable solutions in a collaborative way (Allen, Espey, Marks, & Skipper, 2021). A key aspect is the search for environmental solutions is the assessment of the environmental impact of the materials used in products, which helps to incorporate environmental criteria into the multi-decision process of material selection. In this context, it is essential to develop precise and applicable methodologies for calculating this impact.

The importance of materials in the economy is unquestionable, as they are the essential basis of all the products we use today in our production model. The material selection process in crucial in engineering, construction, and manufacturing (Ashby, 2001) (Ribeiro, Peças, & Henriques, 2013). However, it presents challenges due to the variety of stakeholders and sometimes-contradictory criteria (Emovon, 2020). The material selection process involves identifying and choosing the most suitable materials to meet the specific requirements of a project, considering technical, quality, manufacturing, cost and supply aspects. However, it is becoming increasingly important to also consider the environmental impact of materials throughout their life cycle, i.e. their sustainability (Mesa, 2023).

The importance of an optimal material selection process from the early design stages should not be underestimated, as it can drastically reduce the overall environmental impact of products (Eddy, Krishnamurty, Grosse, Wileden, & Lewis, 2015). Several authors point out that 80% to 90% of the economic and environmental costs of a product are fixed at the design stage (Kengpol & Boonkanit, 2011) (Ribeiro, Peças, & Henriques, 2013). The challenge is not to find the perfect option, but to explore the strengths and weaknesses of each material or design, from multiples perspectives (Shanian & Savadogo, 2006).

Life Cycle Assessment (LCA) is an important tool for material selection, as it allows to evaluate and compare their environmental impact (Margallo, et al., 2021). That contributes to reducing negative impacts on the environment, and also strengthens the resilience of supply chains by mitigating dependency on critical and strategic materials (Ferro & Bonollo, 2019) (Kim, Lee, BumChoong, & Jinsoo, 2019). Material selection is therefore one of the tasks that can have the most influence on the sustainable performance of a product (Mesa, 2023).

1.2. Efficient Resource Management

Furthermore, the efficient management of resources is an issue of global concern (Zhang, Bourdeau, Nwaila, & Ghorbani, 2023), and it is essential for the economic and technological security of the European Union (EU), given its dependence on imports of many of these resources. In this sense, initiatives such as the European Materials Initiative (European Commission, 2024) have been implemented, whose aim is to ensure safe and sustainable access to the materials.

Within this strategy, several mechanisms have been established for the quantification and monitoring of Critical Raw Materials (CRMs). This includes the development of the "List of CRMs for the EU", which is regularly updated (European Commission, 2011) (European Commission, 2023). The materials contained in this list combine raw materials with great economic importance for the European economy and with high supply risk. The EU list is based on a comprehensive and methodological assessment of the supply and demand of strategic materials, as well as the risk factors associated with their access and supply (European Commission, 2017).

The EU recognises the importance of CRM for its transition to a more sustainable economy. These resources are essential for the development of clean technologies and renewable energy (Göçmen Polat, Yücesan, & Gül, 2023) (Rabe, Jostka, & Simth Stegen, 2017), which are key aspects of Europe's strategy to address climate change and promote decarbonisation.

Security of supply of CRM has therefore become a priority for the EU, which has implemented various initiatives and policies to diversify and encourage research and innovation in alternative technologies (Lewicka, Guzik, & Galos, 2021).

Due to the importance of these materials, criticality of materials should be urgently included in the eco-design of products (Ferro, Bonollo, & Cruz, 2021). While there is no specific legislation on the quantification and use of CRM, the European Standard (EN) 45558:2019 "General method to declare the use of critical raw materials in energy-related products" (AENOR, 2019) was published in 2019, with the aim of improving the reuse of components or recycled materials from end-of life products. Increased knowledge of CRM content can contribute to a more efficient management of valuable and scarce resources. In addition, a sustainable design framework for safe and sustainable chemicals and materials from a design point of view has been developed in the EU (European Commission. Joint Research Centre., 2022), which mentions the need to qualitatively consider the presence of CRMs. (i.e., whether they contain them or not). In this framework, it is recommended to monitor the use of these materials with the aim of reducing dependence on these resources.

1.3. Monitoring of environmental impact and CRM content of steel

Previous publications have shown the importance of considering the exact composition of materials for a more accurate calculation of environmental impact, and in addition allowing the quantification of the CRM content (García Gutiérrez, Elduque, Pina, Tobajas, & Javierre, 2020) (Gómez, Elduque, Sarasa, Pina, & Javierre, 2016). It is unusual to find a characterisation of the environmental impact considering the exact composition of the material, and this can significantly influence the environmental impact.

The steel industry is globally essential for industrial development, construction, and numerous economic sectors, having a significant impact on the world economy (Conejo, Birat, & Dutta, 2020). It is an essential material in numerous technological applications and in a variety of industrial sectors, including automotive, energy and general manufacturing (Black, Kohser, & DeGarmo, 2008) (Nezamoleslami & Hosseinian, 2020). In addition, the alloying of steel with small amount of other chemical elements allows for a significant improvement in their properties, conferring them much greater applicability for specific sectors (Xing, Wei, & Hou, 2018). Some of these alloying elements are nowadays considered as Critical Raw Materials for the European Union.

Researchers focusing on the global steel industry have highlighted the importance of LCA in environmental assessment (Burchart-Korol, 2013). Studies often focus on assessing the environmental implications of different steel generation processes. Currently, most of the research on iron and steel production has focused on greenhouse emissions and waste generation (Liu, et al., 2020), and there is extensive research in the field of improving the energy efficiency of its production process (Rojas-Cardenas, Hasanbeigi, Sheinbaum-Pardo, & Price, 2017) (He & Wang, 2017) (Hu & Zhang, 2017), reducing CO_2 emissions (Duan, Li, Mu, & Gui, 2017) (van Dijk, et al., 2017) and recycling steel scrap (Nechifor, et al., 2020).

For all these reasons, a methodology was previously established that incorporates steel composition in the calculation of the environmental impact of these steel grades, and a tool was developed for modelling the LCA of steel as a function of composition, as well as quantifying the presence of Critical Raw Materials (García Gutiérrez, Elduque, Pina, Tobajas, & Javierre, 2021).

The global concern for environmental issues has boosted the development of a multitude of eco-design methods and tools, many of them published in the literature during the last twenty years. However, today there are numerous barriers that prevent a real and effective implementation in industrial sectors, especially in manufacturing companies (Rossi, Germani, & Zamagni, 2016).

These methodologies should be easily applicable by companies, as their incorporation into practical business development can contribute significantly to the reduction of environmental impact and a more efficient resource management. Moreover, the incorporation of theoretical concepts into business practice will promote a more effective transition towards more sustainable and environmentally friendly practices.

Continuing with this line of research, a tool has been developed that allows the calculation of the environmental impact and monitoring of the CRM content of the batches obtained from steels, considering the exact composition of each batch of the material that can be obtained by means of spectrometry analysis. This contributes to a better understanding of the use of CRM, and to a better control of the management of resources (especially the scarce ones) by the companies. This tool allows companies to monitor their real CRM use, and generate annual reports regarding actual environmental impact, and CRM consumption.

The manuscript has been divided into the following sections. Section 2 shows the methodological approach adopted for the development of the CRM content monitoring tool: the objectives pursued, the LCA approach, the data collection process, and the functionalities of the tool. Section 3 shows a case study on the data collection of different batches of steel 1.4301. And finally, section 4 shows the main conclusions of the study.

2. CRM content monitoring tool for Steel

In a previous communication (García Gutiérrez, Elduque, Pina, Tobajas, & Javierre, 2021), a tool for the characterisation of the environmental impact of steel and the quantification of the CRM content was presented. This tool allowed the modelling of a Life Cycle Inventory (LCI) of steel production, based on the composition ranges established by standards. Through this modelling, it allowed the simulation of the environmental impact of the steel alloy based on their composition ranges, as well as its CRM content.

In this communication, different results are pursued:

- On the one hand, to develop a tool that allows the calculation of the environmental impact and the quantification of the content in CRM, given an exact composition of material samples using analytical techniques.
- To obtain a history of the results of the environmental impact and CRM content, allowing the analysis of the consumption of materials in a manufacturing plant, as well as an estimate of the annual demand for CRM.
- Enable the preparation of reports on CRM content, in accordance with the standard 45558 (AENOR, 2019).

With the development of this tool, the following benefits are expected:

- **Improved accuracy.** The use of exact material compositions in the impact assessment tool allows for a more accurate simulation of environmental impact and a proper quantification of CRM content. This is because the specific composition of each steel grade can significantly influence its total environmental impact, as it has been shown in previous studies.
- **Reducing approximations.** The use of databases in LCA modelling can incur approximations that hinder decision-making in product design. By particularising the databases with the aim of obtaining a more accurate calculation, such as the use of the exact composition of steel, these approximations can be reduced.
- **Efficient use of Critical Raw Materials (CRM).** By

assessing the content of CRM and monitoring its consumption over time, the use of CRM can be reduced and the dependence on these materials monitored, contributing to a more sustainable and efficient use of available resources. This tool also allows to generate annual reports that could be used to create a continuous improvement cycle of the environmental behaviour of a company.

2.1. Life Cycle Assessment Methodology

The simulation tool implements a methodology with a strong Life Cycle Assessment (LCA) approach. Although the explanation of this methodology is not the object of this communication, some aspects are explained below.

The LCA has been developed following the steps stipulated in the international standards ISO 14040 (AENOR, 2006) and ISO 14044 (AENOR, 2006) which establish principles, framework, requirements and guidelines for conducting an LCA.

The definition of the functional unit has important implications for the development of an LCA. The production of 1 kg of steel from raw materials, considering the alloy composition, was taken as the functional unit in this study.

The Life Cycle stages considered in this study corresponded to the acquisition of raw materials, the transport of these raw materials to the steelmaking plant and the steel production processes.

For the environmental impact calculations, the Ecoinvent v3.5 database (developed by the Swiss Centre of the Life Cycle Inventories) was used (ecoinvent, 2022). It was calculated according to two environmental impact calculation methodologies:

- ReCiPe 2016 EndPoint (H) V1.03 / World (2010) H/A (Various authors, PRé Sustainability, 2020)
- Global Warming (GWP100y) category from CML-IA baseline V3.05 / EU25 (Leiden University, 2016)

Moreover, the quantification of CRM content has been made based on the latest list published by the European Union in 2023 (European Commission, 2023).

2.2. Data collection process

In order to carry out the calculation of the environmental impact and quantification of the CRM content, it is necessary to collect the composition data. It is essential to collect detailed information of the exact chemical composition of the different batches. This information can be obtained from technical specifications, material certificates or directly from tests on batch samples. Such tests include Optical Emission Spectrometry (OES), X-ray Fluorescence (XRF) or Inductively Coupled Plasma Mass Spectrometry (IPS-MS) (Baral, y otros, 2024).

Once the material compositions have been obtained, these data must be integrated into the tool for calculating the environmental impact of steel and CRM content. In addition, if the composition specification of the material is known (based on standards information), it is possible to check whether the actual composition of the material is within the range established by the standard.

With the exact material composition entered, it is possible to simulate the environmental impact of different types and batches of steel. By using accurate composition data, the simulation will provide more reliable and detailed results on the environmental impact and CRM content of the analysed steel.

Thus, the use of the tool in business practice will begin once the steel batch is received. Using laboratory analytical techniques, the batch composition will be determined and entered into the tool, which will be able to generate the necessary reports on the environmental impact and CRM content of the batch. The annual information could be published in the Corporate Social Responsibility report of the company.

2.3. Tool functionalities

Considering the data flow performed by the tool, the functionalities implemented in the tool are explained below.

2.3.1. Introduction of the batch composition

The user can enter the composition obtained by analysing the chemical composition of the batch. Knowing the composition ranges established by standard for the evaluated steel, the tool indicates if there are discrepancies between the actual composition and the requirements set by the standard. It is sometimes common to find discrepancies between the two results.

For each batch, it is necessary to record the batch reference and the quantity of kilograms of material received at the manufacturing plant. The complete batch information can be recorded to analyse the annual and historical of results.

2.3.2. Results per batch

Once the composition data has been entered, it is possible to visualise the results of the environmental impact per batch. The results can be analysed according to the different calculation methodologies implemented in the tool: ReCiPe 2016 methodology and the Global Warming category included in the CML-IA baseline methodology.

2.3.3. Historical information of the manufacturing plant

The information recorded on the different batches of material can be analysed in an aggregated form, in order to analyse the differences in composition between the different batches, as well as the cumulative use of CRM according to the latest published list by the European Union (European Commission, 2023).

This historical of results can be analysed for the entire production capacity of the plant or considering a specific steel grade. Moreover, knowing the annual demand forecast, it is possible to estimate the use of CRM, according to the previously accumulated CRM consumption.

2.3.4. CRM Reports

Despite the fact that currently there is no legislation that requires the quantification of the content of critical raw materials, the European Standard (EN) 45558:2019 "General method to declare the use of critical raw materials in energy-related products" (AENOR, 2019) was published in 2019.

Based on data entered in the tool, it is possible to generate a report for the communication of the content of CRM in accordance with the standard guidelines.

3. Case study

A case study is shown below, where the differences in environmental impact and CRM content for a stainless steel with the designation 1.4301 has been analysed.

For this purpose, a series of measurements were made on several samples of different batches of this material, using a Spectro Optical Emission Spectrometer, model Spectrotest TXC25 (Spectro Metek, 2024).

To better interpret the purpose of the study, Table 1 shows an example of the measured composition of one of the samples (Batch B), where it is compared with the composition ranges established by the standard. The composition obtained from the analysis complies with the ranges established by the standard, with the exception of the presence of small amounts of other elements, less than 0.37%.

Table 1. Batch B (Stainless Steel 1.4301) composition, compared with standard composition ranges

Element	Standard range	Measurement
Co	-	0.207
Cr	17.5 - 19.5	18.2
Cu	-	0.192
Mn	0.0 – 2.0	1.79
Mo	-	0.365
N	0.0 – 0.1	0
Ni	8.0 – 10.5	8.07
P	0.0 – 0.045	0.019
S	0.0 – 0.015	0.0026
Si	0.0 – 1.0	0.392
Ti	-	0.014
V	-	0.077

Composition obtained from 10088-3 Standard

Figure 1 shows the results of environmental impact per kilogram of material for the ReCiPe 2016 methodology and the Global Warming category of the CML-IA baseline methodology. Also for CRM content of Batch B. These results are compared with the maximum and minimum results that, according to composition standards, could have been obtained. It can be seen that in the case of the ReCiPe 2016 methodology, the environmental impact of steel is close to the maximum values. In terms of CRM content, batch B has a content of 2.5%.

Also, by recording the composition information of 20 different batches of 1.4301 steel, historical of results of CRM content and environmental impact are obtained.

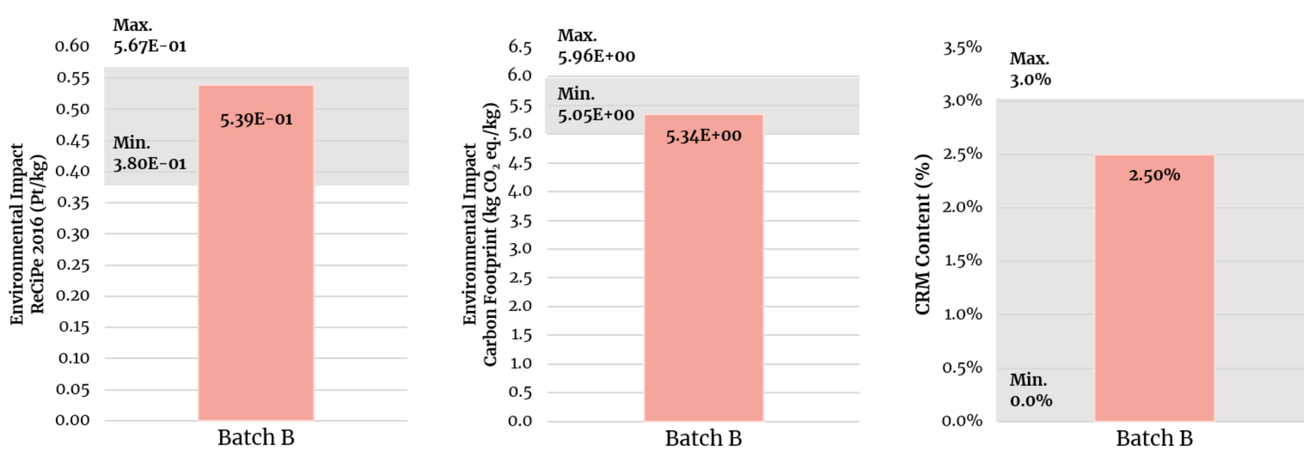

Figure 1. Environmental impacts and CRM content of Batch B

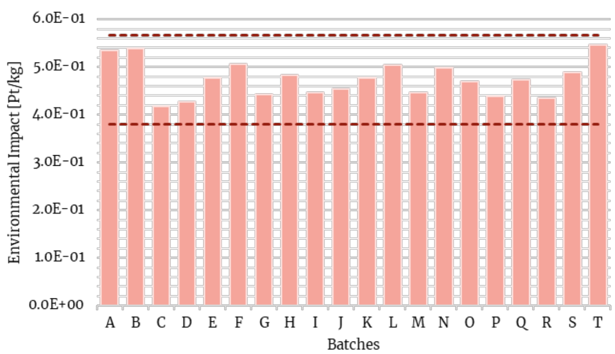

Figure 2. Environmental impact per kilogram ReCiPe 2016 – 20 Batches

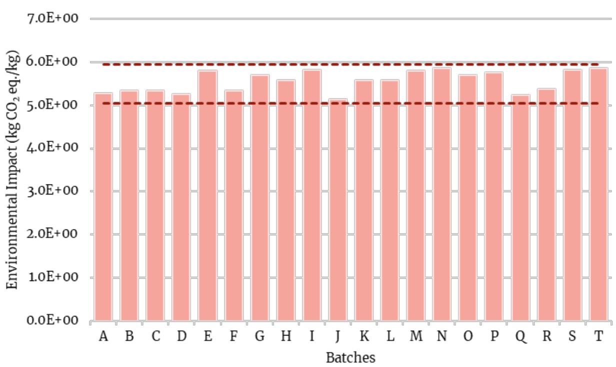

Figure 3. Environmental impact per kilogram Global Warming (GWP100y)– 20 Batches

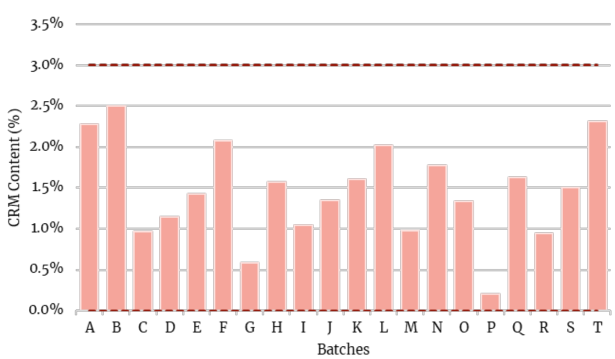

Figure 4. CRM content – 20 Batches

It is also possible to obtain the cumulative consumption of CRM as a function of steel consumption, and to forecast the total consumption of CRM assuming a total annual steel demand, as shown in Figure 5.

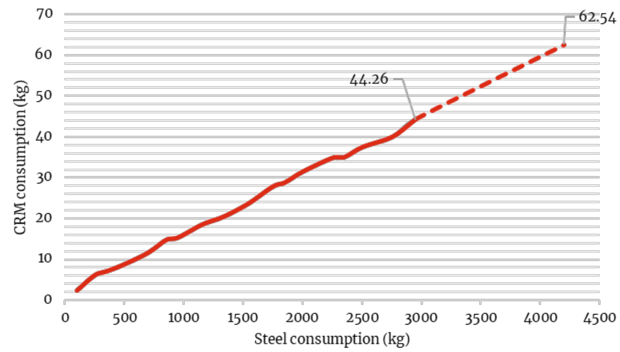

Figure 5. CRM consumption (kg)

4. Conclusions

The incorporation of exact compositions in environmental impact assessments and quantification of CRM content is a significant advance for the sustainability of manufacturing companies.

To this end, a tool has been developed that allows the calculation of the environmental impact and quantification of the CRM content of steel batches, using exact compositions obtained by spectrometric analysis. This tool improves the accuracy of environmental impact simulations and facilitates efficient resource management. The tool not only allows the simulation of the environmental impact of different steel batches, but also facilitates the generation of reports on CRM content. This helps companies to monitor and manage the use of these resources, reducing dependency and promoting sustainability.

As an example to show the potential use of the tool, a total of 20 batches of 1.4301 stainless steel have been considered, showing the variability in environmental impact and CRM content. This kind of tool allows companies to obtain historical results, forecast the annual demand of CRM and make informed decisions on resource management. This tool could also be used to enable comparison between different suppliers for the same steel grade, as some of them could be consistently providing batches with both lower environmental impacts and CRM content.

The main limitation of the tool is that, currently, it can only be applied to steel. It is possible to develop similar tools for monitoring CRM content in materials other than steel, whether metallic or not. Likewise, a tool for monitoring CRM content in complex products could be developed, such as printed circuit boards. The composition information would be obtained in this case from the suppliers' information on the CRM content of the different electronic components.

The developed tool contributes to a better understanding and control of the use of critical resources, supporting the transition towards a more sustainable and efficient production model.

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