Life cycle assessment applied to the cutlery sector in the case of steel-based production

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Abstract. The growing global awareness of environmental problems requires companies to design their production processes to reduce ecological impact and pursue sustainable development. In this rapidly changing context, the transition to a greener economy demands a complete understanding of the environmental consequences of industrial production. In this regard, life cycle assessment has emerged as a critical tool to comprehensively assess the environmental impacts associated with each stage of the product life cycle. Sustainable development addresses many issues, including resource efficiency, waste reduction, and, in general, the minimization of environmental footprints resulting from processes. The LCA approach provides valuable information in this regard, as each stage of a product's life cycle is analyzed, from extraction to final disposal of the material allowing companies to determine which improvement areas are crucial for a more sustainable production. The present study relates to the cutlery market spanning from disposable plastic, cardboard, and bamboo cutlery to stainless steel cutlery. A complete LCA of stainless-steel forks is conducted using primary data from an Italian company. All the production steps will be analyzed, from stainless steel coil to end of life, to highlight the environmental hotspots of each process, such as energy consumption, resource use, and emissions. Based on the results of the LCA, strategies for improvements will be proposed to guide more informed decision-making in industrial production, offering a path toward more sustainable production processes that balance ecological responsibility with operational efficiency.

Introduction

The 20th century witnessed a significant expansion of global production, leading to the rise of the consumer society. In this context, environmental concerns have long been overshadowed by a pattern of living centered on the rapid cycle of consumption, disposal, and replacement, typical of a “throwaway culture.”

However, this approach has increasingly revealed its limitations, with environmental impacts becoming more evident and alarming. In response to these issues, the need has grown for tools that can thoroughly and systematically assess the ecological effects of this production and consumption model. One such tool is the Life Cycle Assessment (LCA).

The LCA methodology originated in the early 1970s to carry out energy analyses. Still, growing interest in this area led, in 1979, to the publication of Boustead and Hancock's handbook, a seminal text on life cycle analysis that, for the first time, introduced a detailed description of all the critical points for the proper conduct of an LCA [1].

The following decade saw the essential development of this analysis, which also began to be applied to other industries to improve their production activities.

The term Life Cycle Assessment was officially adopted only in 1990, during the SETAC (Society of Environmental Toxicity and Chemistry) congress, held in Vermont, USA. On that occasion, Life Cycle Assessment was defined as "a process to evaluate the environmental burdens associated with a product, process, or activity by identifying and quantifying energy and materials used and wastes released to the environment; to assess the impact of those energy and material uses and releases to the environment; and to identify and evaluate opportunities to affect environmental improvements." [SETAC, 1991] [2,3].

At the same congress, the 4-step scheme that still forms the basis of the LCA methodology was presented.

Rapid methodology development in the 1990s led to its standardization in 1997 when the International Organization for Standardization (ISO) published the first standards. These were later updated in 2006 and named ISO 14040 and ISO 14044 [4,5,6].

In 2003, the European Union promoted the use of LCA through its Communication 302, which included it as one of the core principles of Integrated Product Policies (IPPs). This initiative aims to reduce environmental impacts by improving product performance and increasing industrial competitiveness, promoting small and medium-sized enterprises to adopt low-environmental impact practices. IPPs are based on the premise that each stage of a product's life cycle contributes to its overall environmental impact in different degrees and, therefore, must be optimized in an integrated and coordinated manner.

Through LCA, IPPs identify critical areas where action can be taken to improve sustainability, reduce emissions and energy consumption, and manage resource use and waste. This approach avoids shifting impacts from one life cycle phase to another, ensuring a holistic view. In addition, IPPs promote shared responsibility among producers, consumers, and institutions, encouraging eco-design and the production of more sustainable goods that reduce the use of natural resources and facilitate recycling and waste reduction. This initiative is a fundamental strategic approach to improving the environmental performance of products throughout their life cycle [7].

In 2008, the European Union Communication on "Sustainable Consumption and Production" reaffirmed the importance of LCA in promoting sustainable development models. This communication aimed to improve products' environmental performance and facilitate informed consumer choices through clear and consistent labelling [European Commission, 2008].

Today, the LCA method is a valuable tool that can provide objective and scientifically valid results to measure the environmental performance of a specific production chain. It also aligns with the United Nations Sustainable Development Goals (SDGs), providing a methodological framework for measuring and improving the environmental sustainability of products and organizations. The International Organization for Standardization developed the first ISO standards concerned with this topic in 1997 to provide the framework and methodological requirements for conducting LCA scientifically sound and consistently. The official publication of the ISO 14040 and ISO 14044 standards took place in 2006 in Geneva, Switzerland; they were subsequently revised and updated in 2020 to ensure their relevance and accuracy.

The ISO 14040:2006, entitled "Environmental Management — Life Cycle Assessment — Principles and Framework," established the general principles and structure of Life Cycle Assessment. It delineates the four fundamental phases of the analysis:

- Goal and Scope Definition
- Life Cycle Inventory (LCI)
- Life Cycle Impact Assessment (LCIA)
- Interpretation

The present study relates to the cutlery market spanning from disposable plastic, cardboard, and bamboo cutlery to stainless steel cutlery. A complete LCA analysis has been carried out concerning the production chain developed by the long-term established manufacturer Mepra S.p.A., an example of Italian excellence and leader in this field. There is a lack of similar studies in the literature therefore, this study can enhance the state-of-the-art in this field.

Case Study

The Case Study presented here is a practical application of LCA in cutlery production, highlighting its versatility and potential to guide sustainable choices in various industries. While comparing different types of disposable cutlery might make it difficult to establish a clear preference for one material over another, this is different when comparing the latter with those made of stainless steel. In this case, a clear difference in terms of sustainability immediately emerges. Although stainless steel requires high energy consumption in the production phase, its durability and the possibility of reuse over thousands of cycles make this material ecologically beneficial in the long run.

One of the main advantages of stainless-steel cutlery is its ability to be recycled at the end of its life, thus minimizing waste accumulation and using new resources. All this makes it possible to say that this type of cutlery is the most sustainable alternative for long-term use despite the higher production energy expenditure. Among the many stainless-steel variants, 18/10 stainless steel is considered the benchmark for high-quality cutlery production. For these reasons, many companies in the industry have chosen it as the primary material for cutlery production.

This work will focus on 18/10 stainless steel, which Mepra S.p.A. uses for its fork production. In the context of this thesis, dedicated software was used to apply the LCA methodology. SimaPro [version 9.6.0.1. ©2024 PRé Sustainability] was used to model the production process of the stainless steel 18/10 fork batch produced by Mepra S.p.A. to identify critical areas in terms of environmental impact and propose improvement strategies. The first fundamental step in building a model in SimaPro is selecting libraries, which constitute the set of data available in the software.

In the Mepra S.p.A. case study, the Ecoinvent 3 database in its most updated version, 3.10.1, was used. The scheme of the entire production process phases is reported in Fig. 1.

The production process starts with transporting the stainless steel coil to the production line, where it is straightened and blanked to create initial shapes and reduce waste. The pieces are then laminated to adjust thickness, followed by a second blanking for precise shaping. Burr removal is outsourced to ensure smooth edges, after which the forks undergo an alcohol-based washing process. The coining phase shapes the forks into their final shape, with additional outsourcing for deburring ribs and plugs. Automated cleaning and finishing ensure a polished appearance, followed by a final water wash in a closed-loop system. The process concludes with manual quality control to identify and correct any defects.

The chosen functional unit for the LCA analysis is the production batch, consisting of 10,000 pieces; this allows the environmental impacts to be quantified based on a standardized production process output, facilitating comparison with similar processes.

The system boundary is from cradle to gate including the activities within the plant that contribute to the production of the final product, specifically covering:

- Mechanical cold working processes
- Surface treatments to achieve the final product quality
- Energy consumption: the electricity needed to operate the machines involved in production
- Management of waste generated during the process

The system boundaries exclude downstream processes, like packaging, transportation, product use, and disposal. The Life Cycle Inventory (LCI) is based on primary data collected directly from the Mepra S.p.A. production plant, ensuring that the information accurately reflects the manufacturing operations for the stainless-steel forks.

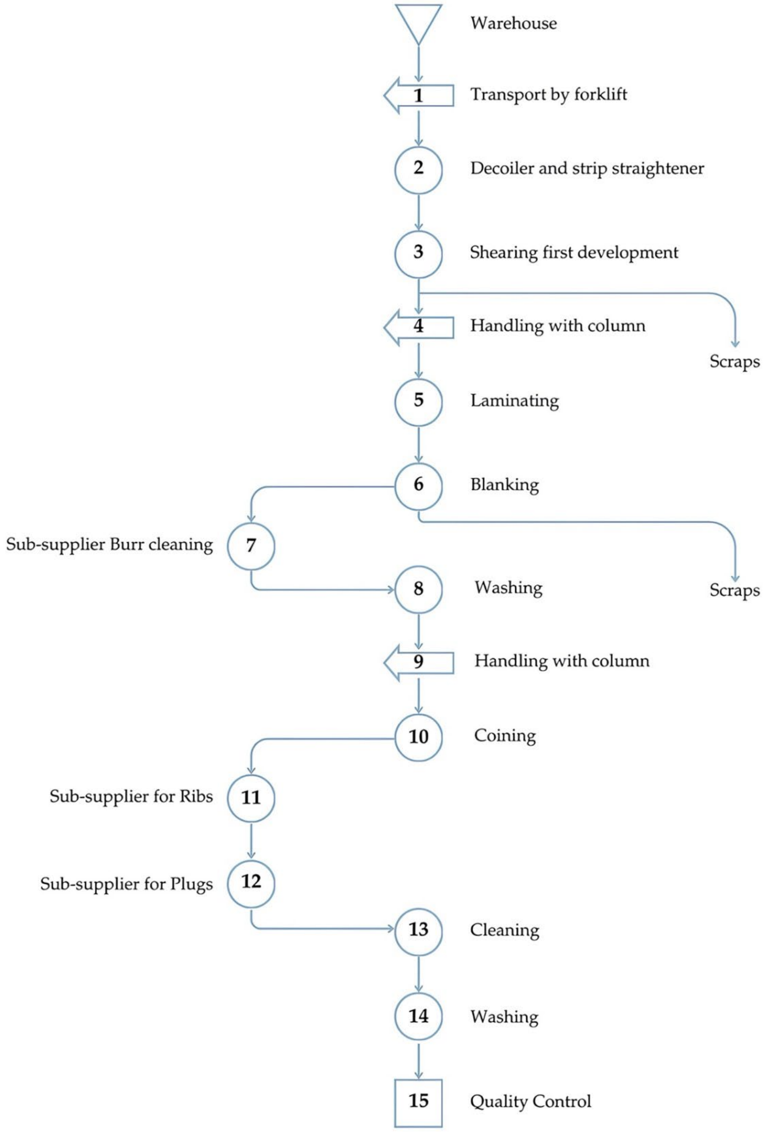

Figure 1 – Production process flowchart

The primary data include detailed input and output for the production batch of 10,000 units, specifically:

- Material inputs: Quantity of stainless steel 18/10 used in production
- Energy consumption: Electricity is used by machinery, and energy is generated from renewable sources like photovoltaics
- Water and lubricant usage: The amount of water used in the final washing stage and the quantity of lubricant oil used in processes 3, 5, 6, and 10
- Waste generation: Types and quantities of waste produced during manufacturing

These primary data were collected for a specific reference period, 2023, ensuring they represent the company's production cycle.

Results

In the LCA analysis of the production process for the lot of 10.000 pieces, the network shown in Fig. 2 is a fundamental tool for understanding the specific contributions of the different process stages and materials. The network displayed was generated using SimaPro software and provides a detailed overview of the material flow, energy use, and resource consumption, alongside the related environmental impacts expressed in terms of Global Warming Potential.

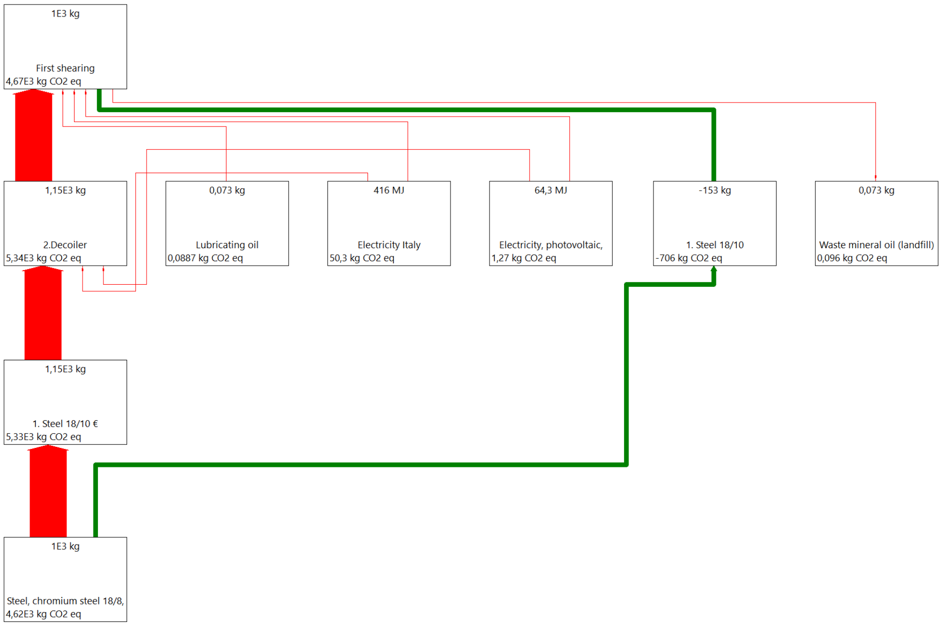

Figure 2 – Network including unit processes from steel production up to the first shearing step.

In the networks generated by SimaPro, material and energy flows are represented by arrows of varying thickness: the thicker the arrow, the greater the process or flow's contribution to environmental impacts. This visualization allows for quick identification of the process stages with the highest impact, facilitating the interpretation of results and the identification of critical areas.

Analysing the network, it is evident that the most significant contribution to environmental impact is linked to the processing of the raw material, specifically stainless steel, which, as previously mentioned, represents the most substantial component in terms of CO_2 equivalent emissions.

To provide a deeper understanding, the analysis focuses on the initial stages of the process, which are crucial for interpreting the entire network.

Fig. 2 illustrates the production process up to the *shearing* first development stage. In addition to the previously discussed impact generated by the steel, additional incoming and outgoing flows can be observed in this stage. The incoming flows include electricity purchased from the grid, electricity generated from photovoltaics, and industrial lubricating oil used in the process.

In the outgoing flows, besides the waste from the disposal of lubricating oil, which has minimal impact on the overall process, there is a green arrow representing 153 kg of steel scrap classified as recycled material. The recycling box shows that the CO_2 equivalent values are negative, highlighting an avoided impact due to material recovery as the steel scraps are assumed to be recycled in closed loop. The network only reports the manufacturing unit processes and does not include the post-consumer end-of-life of steel.

Continuing the analysis, a second significant focus concerns the Blanking stage, shown in Fig. 3. In this phase, the incoming and outgoing arrows represent the electricity consumption from the grid and photovoltaics, industrial oil (which becomes waste after use), and material scraps, totaling 377 kg that contribute to the reduction of the carbon footprint as they are assumed to be recycled in closed loop.

Fig. 4 reports a general overview of the carbon footprint. The stainless-steel production process is the largest source of CO_2 emissions, exceeding 2900 kg of CO_2 eq (including scrap recycling), due to its energy-intensive nature and the use of primary resources like chromium and nickel.

Electricity from the grid is the second major contributor, though its impact is lower as it affects only the operational phases. Photovoltaic energy contributes less, helping reduce the overall impact of purchased electricity. Emissions progressively decrease, with a negative value in the final stage, reflecting an environmental benefit from steel recycling through Mepra’s scrap sales, which offsets part of the emissions from steel production.

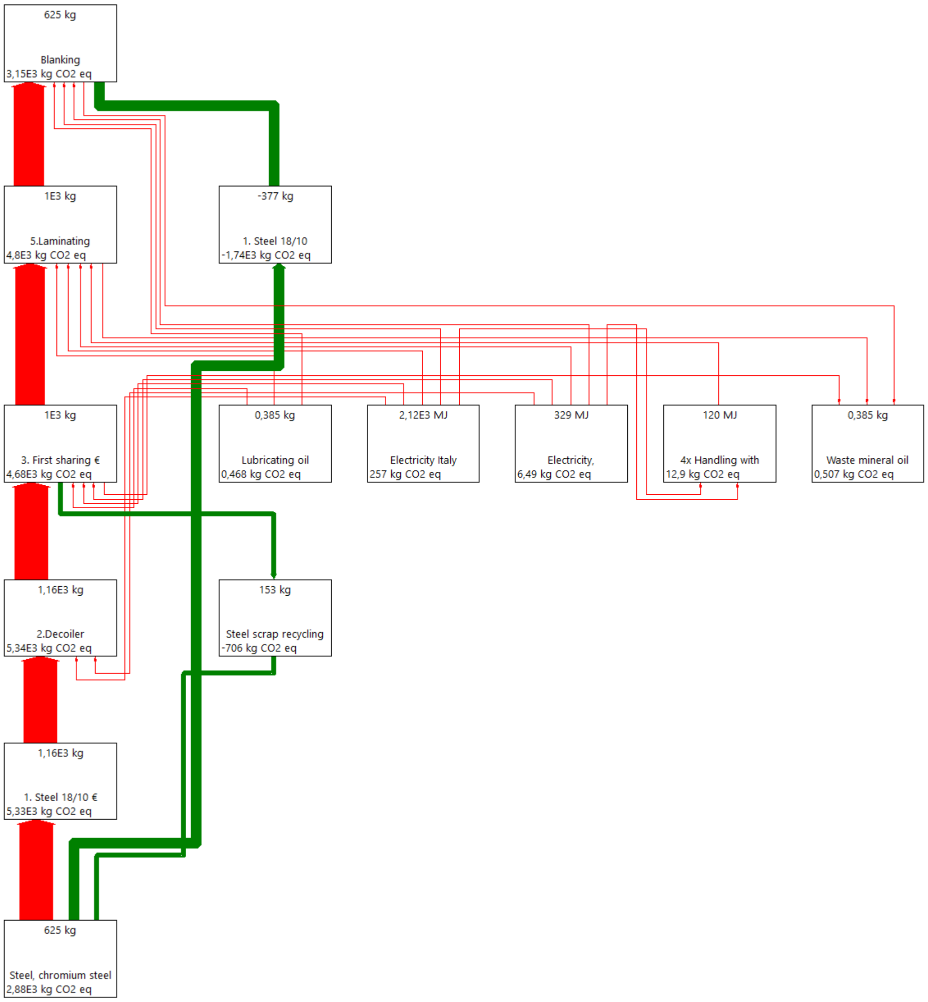

Figure 3 – Network including unit processes from steel production up to the blanking step

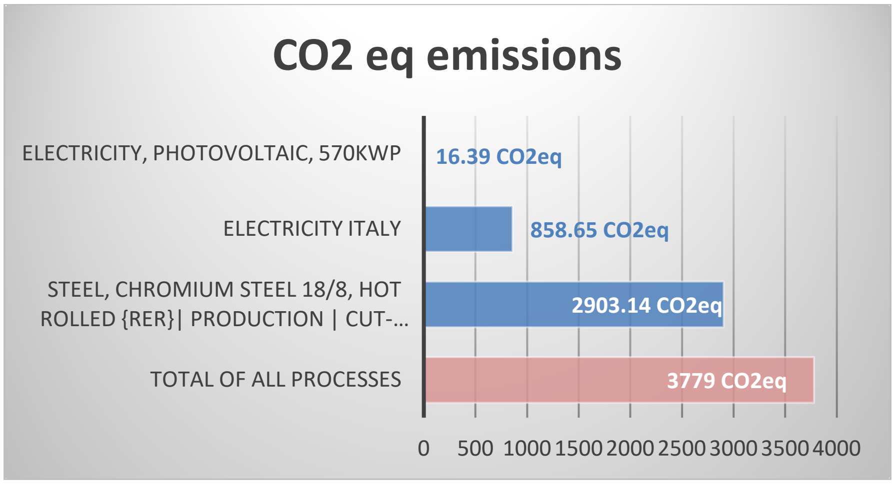

Figure 4 – Global Warming Potential Assessment, method IPCC 2013 GWP 100a. CO2 equivalent emission for the total process production of 10.000 forks (including scrap recycling in closed loop)

Conclusions

The focuses analyzed are essential for understanding the entire network of the production process, as the reasoning applied can be extended to all other phases of the cycle.

In conclusion, by selling the steel scrap for recycling, the company avoids CO_2 equivalent emissions, achieving a substantial environmental benefit. This approach is not the only sustainable measure adopted by Mepra. Beyond recycling, the company has invested in a photovoltaic system that reduces its dependency on the national grid, further decreasing the environmental impact.

Additionally, Mepra has implemented closed-loop processes in the Cleaning and Second Washing phases, reusing modified alcohol and water to minimize waste and resource consumption.

These strategies demonstrate the company's concrete commitment to adopting fundamental principles of a circular economy [8]. These principles aim to minimize resource use and waste production, focusing on material reuse and recycling. Through these solutions, Mepra reduces the overall environmental impact of its production process and promotes a long-term sustainable business model. This approach reflects the company's willingness to continually improve its environmental performance, going beyond mere regulatory compliance and positioning itself as an example of excellence in sustainability and green innovation [9].

Mepra's commitment could be further enhanced by implementing an even more ambitious end-of-life strategy for its products. In a hypothetical scenario where the forks at the end of their life are recycled to produce new forks, the initial impact associated with steel production could be drastically reduced. This approach would virtually eliminate the effect related to raw materials, leaving only the energy consumption and the use of secondary resources such as lubricating oil and water, which would require continuous optimization to improve the efficiency of the production process further [10].

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