Wiebke Hagedorn, Sebastian Jäger, Lucas Wieczorek, Philipp Kronenberg, Kathrin Greiff, Sebastian L. Weber, Arne Röttger

More Than Recycling

The potential of the circular economy shown by a case study of the metal working industry

Originally published in:
Journal of Cleaner Production,
377 (2022), 134439
DOI: 10.1016/j.jclepro.2022.134439

*Wiebke Hagedorn a,b,d,**
Sebastian Jäger b
Lucas Wieczorek b
Philipp Kronenberg b
Kathrin Greiff d
Sebastian L. Weber c
Arne Röttger b

More than recycling – The potential of the circular economy shown by a case study of the metal working industry

a Wuppertal Institute for Climate, Environment and Energy, Wuppertal, Germany

b Lehrstuhl für Neue Fertigungstechnologien und Werkstoffe, Bergische Universität Wuppertal, Germany

c Lehrstuhl für Werkstofftechnik, Ruhr-Universität Bochum, Germany

d Department of Anthropogenic Material Cycles, RWTH Aachen University, Germany

* Corresponding author:
Wiebke Hagedorn
Wuppertal Institute for Climate, Environment and Energy
Döppersberg 19
42103 Wuppertal
Germany

Phone: +49 202 2492-0
Fax: +49 202 2492-108

More than Recycling – The Potential of the Circular Economy shown by a Case Study of the Metal Working Industry

W. Hagedorn
Wuppertal Institute
Department of Anthropogenic Material Cycles, RWTH Aachen University
Fachgebiet Werkstofftechnik, Bergische Universität Wuppertal
Wiebke.hagedorn@wupperinst.org
S. Jäger
Lehrstuhl für Neue Fertigungstechnologien und Werkstoffe, Bergische Universität Wuppertal
jaeger.fuw@uni-wuppertal.de
L. Wieczorek
Lehrstuhl für Neue Fertigungstechnologien und Werkstoffe, Bergische Universität Wuppertal
wieczorek.fuw@uni-wuppertal.de
P. Kronenberg
Lehrstuhl für Neue Fertigungstechnologien und Werkstoffe, Bergische Universität Wuppertal
kronenberg.fuw@uni-wuppertal.de
K. Greiff
Department of Anthropogenic Material Cycles, RWTH Aachen University
Kathrin.greiff@ants.rwth-aachen.de
S. Weber
Lehrstuhl für Werkstofftechnik, Ruhr-Universität Bochum
weber@wtech.rub.de
A. Roettger
Lehrstuhl für Neue Fertigungstechnologien und Werkstoffe, Bergische Universität Wuppertal
roettger.fuw@uni-wuppertal.de

Highlights

- The steel industry misses a great potential offered by the Circular Economy while focusing on recycling only
- Rethinking production chains of steel products such as a machining knife offers environmental saving potential
- Implementing the strategies of slowing, closing, and narrowing in the case study of a machining knife improves its environmental performance and material efficiency
- Auxiliary processes can significantly reduce the environmental benefits

Abstract

The steel industry is responsible for a quarter of all industrial greenhouse gas emissions. So far, the environmental savings are mainly due to steel recycling.

Besides recycling, the circular economy offers strategies to increase material efficiency and thus decrease the primary raw material demand. However, the potentials remain unexploited because circular economy concepts with a higher degree of circularity are not considered. The presented case study of an industrial machining knife illustrates how the production process can be improved by implementing various circular strategies. The environmental performance is analyzed by calculating and comparing the carbon footprint, the cumulative energy demand and the material footprint, and the material efficiency indicator. The results show that the implementation of the three overarching strategies of the circular economy - narrowing, closing, and slowing – contributes to a significant increase in material efficiency. The implementation also has a positive effect on the overall environmental performance. The circular production processes require less energy and resources and cause fewer emissions. Auxiliary processes such as additional transport routes are relevant, as they can reduce or even overcompensate for savings. These processes must be adequately considered and designed.

Keywords: Circular Economy; Steel; Circular Products; Case Study; Environmental Assessment; Material Efficiency;

Abbreviations:

Abbreviation	*Definition*
CE	Circular Economy
CED	Cumulative Energy Demand
CF	Carbon Footprint
Days	d
EAF	Electric Arc Furnace
EoL	End-of-Life
eq	equivalent
GHG	Greenhouse Gas
hours	h
IPCC	The Intergovernmental Panel on Climate Change
kg	kilogram
LCA	Life Cycle Assessment
MF	Material Footprint
Mt	Million tons
mm	Millimeter
PM	Pulver metallurgical Process
SI	Supporting Information
t	tons
mass%	mass-percent

1 Introduction

It is half-time to achieve climate neutrality by 2050 to tackle the climate crisis. Moreover, research shows that previous measures are insufficient to meet this target (UNEP, 2021). The steel industry is of great importance regarding the climate crisis as it is responsible for a quarter of all industrial greenhouse gas (GHG) emissions (Allwood et al., 2011; Ito et al., 2020). In 2018, the global steel use counted 1.8 billion t (worldsteel, 2019a). Thus, it forms the most significant mass flow of metallic resources. On average, one ton of steel causes 1.8 t CO_2 equivalent (CO_2 eq) (worldsteel, 2019b). With an annual production of approx. 41 Mt of crude steel in 2021, Germany belongs to the ten biggest steel producers in the world and is the largest in the European Union (26% of European crude steel production) and causes immense pollution (worldsteel, 2022).

The steel industry can look back on a long history of recycling, a core principle of the circular economy (CE), promoting and resulting in significant resource and emission savings: Secondary steel production is related to three times fewer emissions than primary steel production (Flint et al., 2020). Nevertheless, there are doubts if future steel production can be covered entirely by secondary material due to the limits of recycling, such as quality losses due to contamination by e.g., copper and stock dynamics (Daehn et al., 2017; Haupt et al., 2017; Xylia et al., 2018). Also, recycling will always require energy and primary material as it goes along with dissipative losses, waste generation, and side products, resulting in continuing environmental impact (UNEP, 2013). It is known that a combination of comprehensive energy and material efficiency measures is necessary to substantially cut the environmental impact of the steel industry (Pauliuk and Heeren, 2020).

Despite these limits, the focus remains on the well-known paths of recycling and recovery (Branca et al., 2020). However, recycling addresses only "closing" as one of the three strategies of the promising CE. The narrowing and slowing strategies offer further product-level approaches to increase resource efficiency and reduce environmental impact (Bocken et al., 2016; Potting et al., 2017).

Flint et al. (2020) stresses the poor resource efficiency in the production of flat steel products in Europe with the manufacturing as a hotspot. The authors demonstrate the potential of scrap diversion followed by its usage for other applications, which avoids remelting and reduces the demand for steel production by increasing the production yield. The implementation in the European automotive industry alone could save up to 171 kt CO_2 eq annually (Flint et al., 2020). The analysis is carried out on a theoretical level and with a focus on fabrication scrap. Case studies are needed to evaluate the feasibility, determine realistic saving potentials and decisive influencing factors (Cullen, 2017; Kirchherr et al., 2017; Saidani et al., 2019). Also, literature shows that old scrap forms the major scrap stream in terms of mass in Europe (Rostek et al., 2022). The question arises whether the concept is also applicable to flat products at its End-of-Life.

In addition, such reworking requires a geometric compatibility of components, which makes parts of the scrap unsuitable as the steel components are too small (Brütting et al., 2019; Flint et al., 2020). Many shaping processes, which are relevant in the metalworking industry, such as turning, milling, grinding, and drilling result in waste streams with small particles such as metal chips and grinding sludge. The German metalworking industry produces approximately 1.5 Mio t of metal chips and 280 kt of grinding sludge annually (Reschke et al., 2019). Especially for the latter, there are no established waste treatment options, which focus on obtaining the high value and functionality of alloying elements. There is the option to use it as an input in the cement industry (Reschke et al., 2019). Here, the steel does not have its original function and is no longer accessible to future users, thus it is dissipatively lost (Beylot et al., 2021). This requires technical solutions to make use of the valuable materials bound in the waste stream (Hankel et al., 2020; Jäger et al., 2021).

This paper presents a case study of an industrial machining knife to illustrate how CE strategies apart from recycling and recovery can be implemented in a production chain of a steel product. It offers insights into the results of three research projects, which adapted a production process according to the CE in the metalworking industry: Axial ring-rolling was implemented to produce raw products close to their contour, which narrows the required steel input and shortens the shaping processes. Further, a treatment of grinding sludge was developed and implemented on industrial level to obtain the steel chips, which can be used in powder metallurgy. Lastly, the scrap diversion at the EoL was put into practice to produce another machining knife. The adaptions are analyzed regarding their influence on the environmental performance to test the premise of the CE as being environmentally beneficial.

Thereby, the questions to be answered are:

(1) How does the implementation of CE strategies to the production process of an industrial machining knife influences its material efficiency and environmental performance?

(2) What factors significantly influence the potential environmental savings?

(3) How do the considered indicators correlate?

First, the method to evaluate the industrial machining knife case study is presented. The procedure of conducting the Life Cycle Assessment and chosen material efficiency indicator is explained, and the production cases are introduced in Chapter 2. It is followed by the results of the environmental analysis in Chapter 3. The findings are discussed in Chapter 4, and conclusions are drawn in Chapter 5.

2 Method & Case Study

The life cycle assessment in this study is based on a case study of an industrial machining knife as Fig. 1 illustrates. The steel product and its production process are the subjects of three research projects that implement circular approaches in corporation with the manufacturer to increase resource efficiency. The data used and presented within this article result mostly from measurements, data collection of existing processes, and trial runs (Hagedorn et al., 2020; Hankel et al., 2020; Jäger et al., 2021). The German manufacturer requires 4,575 t of steel annually for this segment of industrial machining knives. The initial situation shows that only 20 mass% of the steel input remains in the final product, illustrated in Fig. 2. Taking the End-of-Life (EoL) into account, only two mass% of the material is even used during the product's lifetime of 5 to 10 d, i.e., dissipatively lost in resharpening processes. These numbers stress the potential and need for improvement. First, the methodology and the scope of the study are described. The outline of the production scenarios, including the circular interventions, follows. Further, it includes relevant information for modelling the scenarios.

Fig. 1 Industrial machining knives in various sizes. (TKM, 2022)

2.1 Goal & Scope

The ISO 14040/14044 is the basis for the performed life cycle assessment (EN ISO, 2020a, 2020b). The goal is to quantify the effect of circular interventions on the environmental performance of producing a machining knife with a diameter of 871 mm, weighing 17.5 kg. The machining knife is used for cutting tissue paper. In the use phase, it rotates on a shaft, cuts the paper at the bottom, and sharpens the opposite cutting edge at the top. The resharpening causes the dissipative losses of material. Resharpening is necessary because the cutting process is subject to high wear, which is associated with a blunting of the cutting edge and a decrease in the cutting performance. Next to the conventional, three new production routes developed according to CE strategies are analyzed, which is part of Chapter 2.4. All adaptions are part of research projects and were realized as test runs on an experimental scale. The use-phase and EoL of the main product are considered unchanged because the adaptation does not affect the material composition, mechanical properties, and utility. The mechanical properties were tested within metallurgical experiments before and after the use phase and showed no changes compared to the conventional process. The scope is limited to a cradle-to-gate perspective.

Some materials and process steps that are not directly related to the manufacturing of the knife and have a minor influence are excluded. This applies to machines for quality control, the working environment, and production. In particular, the machines used to manufacture products have a long useful life and manufacture various products. Allocation to a single product also leads to an insignificant tolerable error in this consideration. Furthermore, the transport of the end product to the customer is not considered, so only the influence of reverse logistics for one circular intervention is considered. This consideration also has implications for transport and distribution in general. The cut-off approach is used to allocate secondary material (Nicholson et al., 2009). The influence of the share of steel scrap was tested and discussed on a general level and, for the case of processing, the grinding sludge.

2.2 Impact Categories

The analysis includes the impact categories of GHG emissions, energy demand and resource use. This is since the steel industry is carbon, energy, and resource-intensive. Former is displayed by the carbon footprint (CF) calculated according to the characterization factors for GWP 100a provided by the IPCC. It is complemented by the cumulated energy demand (CED), calculated according to the energy accounting method KEA. The Material Footprint (MF) was used to analyze the natural resources used. The MF is based on the MIPS approach (Saurat and Ritthoff, 2013; Wiesen et al., 2014). The MF includes all biotic and abiotic materials extracted from nature (Liedtke et al., 2014). Additionally, the indicator of material efficiency was calculated (Reinhart et al., 2011). It is included as the adapted production routes are seen in the CE context, which aims to increase material efficiency. Whereas the MF sums up all resources somehow moved from its natural state in an absolute value, the material efficiency is a relative indicator. It sets the sum of material inputs and waste streams of a process against the product as an output. Accordingly, it shows the yield of a production process.

2.3 Data

The data for the calculations are based on primary and secondary data. Primary data are extracted from the machinery of the project partners. It allows the quantification of material and energy inputs for processing semi-products, which also regard the heat treatment and grinding. Further data regarding the distribution are provided by the internal sales systems, which is relevant for reverse logistics. Also, packaging material was provided, which was disassembled, weighted, and defined by material types. The result is a detailed bill of material. The semi-product producer provided general information regarding the production place and route, which was complemented with data from the literature. The resulting data from the life cycle inventory phase are used within the following impact assessment, which was performed with the OpenLCA software and the ecoinvent database 3.6 (Ciroth, 2007; Wernet et al., 2016).

2.4 Production Routes

In the following, the linear production route is described as shown in Fig. 2 as the status quo in Chapter 2.4.1. It consists of the production of the raw product, the processing to the machining knife and the use-phase followed by the EoL. The former includes the crude steel production and forming processes to receive a circular blank. It is sent to the manufacturer which shapes and hardens it with multiple heat treatment and grinding processes. After the global distribution, the product is used for cutting tissue paper on an industrial scale and then sent to recycling. Also, the circular adaptions are described: The material input is reduced by implementing the axial ring-rolling, which fundamentally changes the production of raw product as shown in Chapter 2.4.2. It is followed by the adaption of making use of the waste stream grinding sludge, which is part of Chapter 2.4.3. The third adaption is according to the implementation of remanufacturing. It includes the returning of larger machining knives at their EoL to produce smaller. It replaces the production of raw product and it makes the heat treatment redundant as shown in Chapter 2.4.4. The descriptions include relevant assumptions, which are fundamental for the calculations. These production routes also form the scenarios, which are further analyzed and listed in Tab. 2. Further details are given in the supplementary material.

2.4.1 Linear Production Route

This production route is the reference system and in Germany. The machining knife is made from ledeburitic cold work steel (AISI D2). The result of its characterization is shown in Tab. 1. This high-alloyed steel is wear-resistant material and goas along with low cutting-edge wear. This results in a low need for regrinding and prolongs the service life of the knives. Its nominal chemical composition results from measurements within the projects and is listed in Tab. 1.

Tab. 1 Nominal and measured chemical composition of the ledeburitic cold work tool steel AISI D2 (X153CrMoV12); the chemical composition was measured by OES in mass%.

Elements in mass%	**C**	**Cr**	**Mo**	**V**	**Si**	**Mn**	**P**	**S**

measured chemical composition	1.53	11.34	0.70	0.70	0.60	0.48	0.020	0.020
Nominal chemical compositon	1.45-1.60	11.0-13.00	0.70-1.00	0.70-1.00	0.10-0.60	0.20-0.60	max. 0.030	max. 0.030

The steel production takes place in an electric arc furnace, according to Baracchini et al. (2018). The input includes 95 mass% steel scrap and 5 mass% of ferroalloys. The smelting process is followed by casting and hot rolling and aims to receive plates. Blanks were removed from the semi-finished products produced by laser cutting. The production yields are considered according to the literature and statements of the supplier (Baracchini et al., 2018; Cullen et al., 2012). Thereby, different laser cutting processes and parameters were tested (SI). As an assumption, parameters were considered to represent a mixture of laser cutting processes (YAG, CO_2).

The formed sheets have anisotropic properties due to their solidification from the melt, characterized by randomly orientated grains. This anisotropy is to be reduced by cross-rolling processes (Kronenberg et al., 2022). After cross rolling, laser cutting separates circular blanks from the sheet. The amount of scrap produced during the beforementioned process steps can be directly remelted. Various drill holes are then inserted into the blank for application and transport purposes resulting in small amounts of waste. However, the metal chips are mixed with cooling lubricants, which requires waste treatment.

Then, the circular blanks are quenched and tempered to adjust the required material properties concerning hardness, strength, and toughness (Bargel and Schulze, 2012; Berns, 1977). In this process, the blank is austenitized at 1100 °C (Oppenkowski, 2011). To counteract oxidation of the blank surfaces, the austenitization process is performed in an inert gas atmosphere. Then, the blanks are quenched to room temperature by rapid cooling. Afterward, the blanks are three times tempered in the regime of secondary hardness at 530 °C for 4 h, (Oppenkowski, 2011). Between the tempering processes, the knives are air-cooled to room temperature. The described heat treatment requires a significant amount of electric energy.

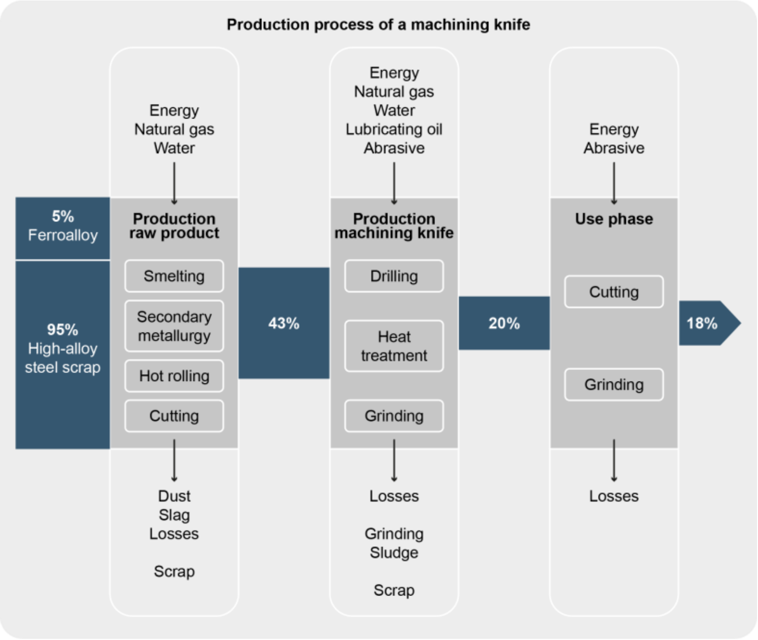

Fig. 2 Production process of an industrial machining knife. (Own data and graphic)

After setting the mechanical properties of the material, a robotic-driven shaping and sharpening process takes place in several grinding steps. It requires electric energy, abrasive material, lubricating oil, and water (Linke and Overcash, 2012; Murray et al., 2012; Silva et al., 2015). A high amount of steel is removed in small hook-shaped grinding chips by grinding wheels with corundum particles (10 kg/component). During the grinding, the formed grinding chips are mixed with corundum abrasives (11-13 kg/component) and cooling lubricant (Raimondi et al., 2012). The cooling lubricant consists mainly of freshwater and a small amount of synthetic, water-miscible lubricating oil (3 g/component). The formed grinding sludge, consisting of metallic grinding chips, corundum particles, and cooling lubricant, leaves the system as a costly waste stream, deposited under strict environmental guidelines. The various shape and sharpening processes reduce the weight of the blank by up to 50 mass% to a sharp machining knife as illustrated in Fig. 2. Comparing it to the initial input of the steel production, 20 mass% end up in the final product. The continuous resharpening processes reduce the weight of the machining knife in the use-phase so that most of the product is sent as scrap to recycling at its EoL.

The energy mix for the heat treatment and grinding processes are adapted as the producer purchases electricity with a higher share of renewable energy than the average energy mix in Germany. Its influence on the results is tested (SI). Further, the final packaging of the knife is included. It allows multiple usages, weighs 2 kg, and consists of numerous components and materials (SI).

2.4.2 Reducing Material Input (Narrowing)

During semi-product production, 57.1 mass% of steel results as scrap, which must be remelted. Then, 50 mass% of the circular blanks is ground off during final processing. Around 20 mass% of the crude steel ends up in the product, indicating poor material efficiency. Radial-axial ring rolling offers a promising solution to improve this inefficient process. The new production process makes it possible to produce a circular blank close to the final geometry. It minimizes the material input and waste. Thus, it is in line with the CE strategy narrowing as it reduces the material required per product use (Bocken et al., 2016).

Forming production processes are characterized by pictorial shaping and volume constancy. In this example, a disc should be produced. The discs are then used as semi-product for the machining knives without producing a material surplus. The process leads to a lower amount of grinding sludge in the subsequent process steps because the blank can be rolled closer to the final contour. The challenge can be found in the ratio of the relatively large surface area to the total volume of the workpiece. Also, the radial-axial ring rolling requires heating (Lohmar et al., 2020) so that the necessary forming forces are kept low by reduced flow stresses of the material. Insofar as there are sufficiently high temperatures during hot forming, the hardening process can be integrated into the forming process, if a sufficient cooling from the process heat is performed.

This adapted production of circular blanks has the lowest development level. No robust data are provided from the production plant testing the developed process. The smelting process is still required, but less steel has to be used. The material inputs scrap and ferroalloys are reduced by 61.6 mass%. This also leads to reducing other input and output flow, such as energy. The hot rolling (radial-axial ring-rolling) follows the smelting process. The energy required for radial-axial ring rolling is likely in the same range as the conventional hot rolling process. The hot rolling process is assumed to represent the new process. The laser cutting processes can be neglected because the required geometry is achieved by the radial-axial ring-rolling. A CAD modelling within this study shows the decreased weight of 19.5 kg for the circular blank, which is the output of the process. The transportation of semi-products considers this reduced weight. The resulting circular blank still requires a heat treatment to adjust the required material properties. This heat treatment remains unchanged. The grinding process is shortened as it depends on the material removed, and less material must be removed to achieve the geometry of the knives. The material and energy inputs and waste streams are reduced accordingly. The final product is equal to the status quo regarding its geometry, material properties, and functionalities.

2.4.3 Waste becomes Resource (Closing)

The chipped grinding swarf of the shaping processes is the most significant waste stream, mixed with abrasive particles from the grinding wheel and cooling lubricant. Waste and disposal laws consider it environmentally critical due to its contamination with cooling lubricant. Previous preparation steps for the treatment of grinding sludge are based on recycling the cooling lubricant (Brinksmeier et al., 2001, 1994). Filtering or briquetting systems are used for this procedure. There are recycling methods that provide use of the grinding sludge, e.g., in cement production. It is used as a mixture of components without considering the high quality of the individual components. Within one of the research projects, the possibility of specific steel chip reuse is investigated (Hankel et al., 2020; Jäger et al., 2021). Therefore, the focus is on separating and fractionating the grinding sludge into single-variety components. The resulting steel chips can be used as a raw material for powder metallurgy (PM) production of new products (Hankel et al., 2020; Jäger et al., 2021). This treatment aims to use a waste stream and, with that, substitute the demand for primary material in the field of PM. It corresponds with CE strategy closing (Bocken et al., 2016).

The production process remains unchanged but includes the additional processing of the grinding sludge. The absolute amount of 20 kg sludge results from grinding a machining knife of 871 mm. The weight excludes the cooling lubricant used for grinding as the sludge is air-dried. The remaining minimal amount of lubricating oil is negligible. 47.5 mass% are steel chips. By applying a magnet separator and sieving, 14 mass% (1.4 kg) are directly usable. This 1.4 kg of steel can be seen as a by-product as it can form the material input for PM processes such as hot-isostatic pressing. Some experiments showed that applying further processes such as ball milling reduces the remaining steel chips' size, whereby the chips' yield can be increased up to 64 mass% (6.4 kg). This latter additional treatment of chips was tested experimentally but had high remaining insecurities. Still, the maximum yield of the steel chips is tested to show potential savings.

The steel chips can replace metal powder for PM processes. The commonly used metallic powders are produced by energy-intensive processes like wet and dry reduction, electrolysis, and mechanical separation without and with phase transformation (water- or gas-atomization). In literature, energy intensities are calculated theoretically but not published as absolute values. The energy intensity for gas-atomization of steels varies depending on the size of metal particles required and the alloying concept and ranges from 2.7 MJ/kg to 28 MJ/kg (Azevedo et al., 2018). In contrast, water atomization requires an energy of 3.6 to 11.7 MJ/ kg (Azevedo et al., 2018).

By processing the grinding sludge, which is a waste stream in the production of the machining knife, it becomes valuable output and by-product. The process is thus multifunctional, and the impacts are mass-based allocated as it lacks representative data for proper system expansion (EN ISO, 2020b; Hauschild et al., 2018). So far, the production process provides a machining knife weighing 17.5 kg. The adaption of the production process also results in 1.4 kg (min) to 6.4 kg (max) of steel chips usable for PM processes. The environmental impact is assigned to both products accordingly.

2.4.4 Scrap becomes Product (Slowing)

Another potential regarding the production routes for machining knives lies in the EoL. Currently, it ends up as scrap and enters open-loop recycling. Open-loop recycling faces limitations and is associated with high energy and resource use to adjust the smelt with alloys (e.g., Cr, Mo, V, Mn), thus achieving the required chemical and mechanical properties. At the EoL, most of the high-quality steel of the knife remains unused and allows a second utilization phase as only a small part of the knife is used during the utilization phase. It allows producing a smaller from a worn larger machining knife, which corresponds with the concept of remanufacturing. This leads to avoiding the open-loop recycling and its losses. The worn product is returned instead of disposed at the EoL and substitutes the blank as a semi-product.

This leads to changes in the production process. The production of semi-products, including steel production and hot rolling, can be avoided. An added process is transportation for returning the machining knives at their EoL. To include realistic transportation, the manufacturer provided sales data differentiated by nation, distance, and likely transport mode. Different transport scenarios were formed to illustrate the environmental influence of auxiliary processes as explained in Chapter 2.5. The increased weight of the packaging material and the larger machining knife is considered in these scenarios.

After the transportation, the diameter of the larger machining knives is reduced by laser cutting. This equals the laser cutting in conventional production. The heat treatment can be neglected because the starting material is still in heat treated condition. The grinding process is shortened as less material needs to be removed. The returned knife weighs 23 kg and is ground to the machining knife weighing 17.5 kg. The amount of material removed is reduced by 45 mass% compared to the conventional production process. The reduction applies to the material and energy input of the grinding process.

Tab. 2 Overview of the analysed Production Routes

Route	Acronym	Main Characteristic
Linear	Linear	Linear/conventional Production
Narrowing	Narrow	Radial-axial ring rolling
Closing	$\text{Close}_{\text{Min}}$	Using grinding sludge to produce material input for PM processes with a minimum yield (14%)
Closing	$\text{Close}_{\text{Max}}$	Using grinding sludge to produce material input for PM processes with a maximum yield (64%)
Slowing	Slow_{Av}	Remanufacturing with the larger machining knife at EoL is returned from the average distanced customer
Slowing	Slow_{Min}	Remanufacturing with the larger machining knife at EoL is returned from minimum distanced customer
Slowing	Slow_{Max}	Remanufacturing with the larger machining knife at EoL is returned from maximum distanced customer

2.5 Sensitivity

Within the iterative calculation process of assessing the four production routes, the need for testing specific parameters and their influence on the environmental impact became apparent. One example is the lack of information regarding the cutting machinery for separating blanks from steel sheets in the linear production scenarios. Different alternatives were tested. As the influence and variance are insignificant, a combination was chosen (see SI).

Another process, which was tested, is steel production. Studies show the relevance of the production site, the related energy mix, the production route, and the ratio between primary and secondary material (Haupt et al., 2017; Li et al., 2018; Teubler et al., 2019). The assumed scrap content is higher than the average market values, such as 37% globally (worldsteel, 2019b) and 43.7% in Germany (WV Stahl, 2020). Therefore, the environmental impact of steel production was tested according to the production route, the share of secondary material, and energy mix (SI).

As aforementioned, the manufacturer purchases an electricity mix with a higher share of renewable energy than Germany's average national energy mix. The electricity mix was individually adapted to reflect this. Also, the manufacturer carries out two energy-intensive processes, heat treatment and grinding. The influence on the environmental impact of those processes was analyzed as well.

Another change in the production route, which is subject to variation, is the auxiliary transportation process to return the machining knives for remanufacturing (slowing). The manufacturer provided sales data differentiated by nation, distance, and likely transport mode to include realistic transportation. Different transport scenarios were considered to illustrate the environmental influence: the minimum distance by land ($Slow_{Min}$), the maximum distance by sea, the maximum distance by air ($Slow_{Max}$), the average global transport ($Slow_{Av}$), and the average European transport. The maximum and average scenarios include various transport modes (SI). The increased weight of the packaging material and the larger machining knife is considered in these scenarios.

3 Results

The conventional cradle-to-gate production of one machining knife (linear) has an impact of 106 kg CO_2 eq (CF), requires 1,015.2 MJ eq (CED), and 1,067.6 kg of resources (MF) as the results in Fig. 3-5 and Tab. 3 show. The main contribution to the aforementioned impacts can be traced back to the steel production, the grinding process, and the heat-treatment. The packaging, the laser cutting, and the transportation have a minor impact. It is noticeable that the energy-intensive heat treatment and grinding have a low relative share in the MF compared to CED and CF.

Most of the considered production cases lead to reducing the CF, CED, and MF. The application of the ring rolling (Narrow) is related to reduced environmental impact. All three environmental categories are more than halved as shown in Tab. 3. Considering the grinding sludge as a resource for PM processes (Close) also results in environmental savings. The reduction depends on the output quantity of the metal chips. If 1.4 kg of steel chips can be generated, the impact for one machining knife is decreased by 8%. If 6.4 kg is generated, a reduction of 36.6% in all three environmental impact categories (CF, CED, MF) is achieved. The highest reduction in all three categories is reached by implementing the remanufacturing (Slow) with minimum transportation, i.e., best-case. It is followed by Slow_{Av}, which results in the second-highest reduction in all three categories. An ambiguous result shows Slow_{Max} including air freight as a transportation mode. It can be considered as a worst-case scenario, whereby the transportation route leads to an increase in CF, which fully compensates the high decrease of CF in the production. The CED compared to the Case Linear is slightly reduced but much higher than the other variation of slowed Cases. The MF is slightly higher than Slow_{Min} and Slow_{Av}, but still highly decreased compared to the linear reference production.

All three adaptions are implemented in the CE context, aiming to increase material efficiency as shown in Tab.3. The latter was calculated for all four production scenarios. Within the conventional production route (Linear), 12.5% of the material inputs end up in the product. Producing the semi-product close to the required geometry (Narrow) results in the highest material efficiency (44.1%). Thereby, less amount of material must be cast and removed by grinding. The increase in material efficiency is achieved by reducing material input and waste stream while the outcome is unchanged. The remanufacturing (Slow) also increases material efficiency (40.4%). It reduces material input, i.e., steel, abrasives, and waste streams. The extraction of metal chips from the grinding sludge (Close) increases usable products as output and reduces the amount of waste streams. It leads to the smallest increase in material efficiency (13.6-17.8%). The relative contribution on the process level show that the adaptions address the hotspots. All adaptions result in a decreased CF, CED, and MF for the steel production and grinding process. For the Case of Slowing, a new potential hotspot arises for the CF and CED by the additional transportation.

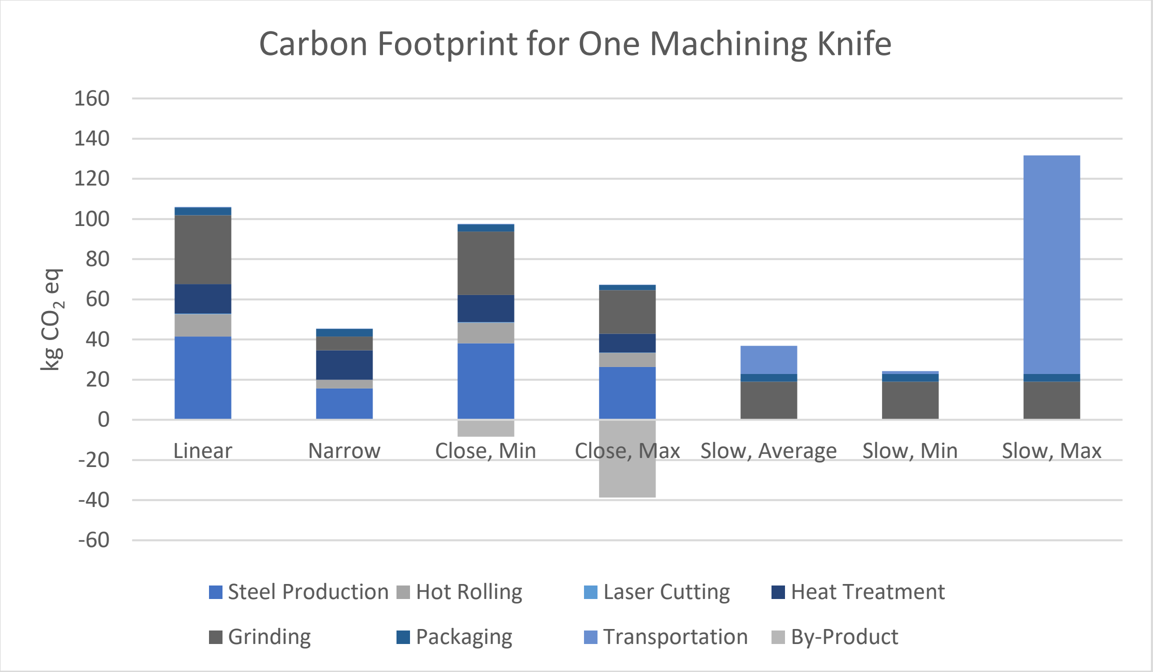

Fig. 3 Carbon Footprint of different Production Cases.

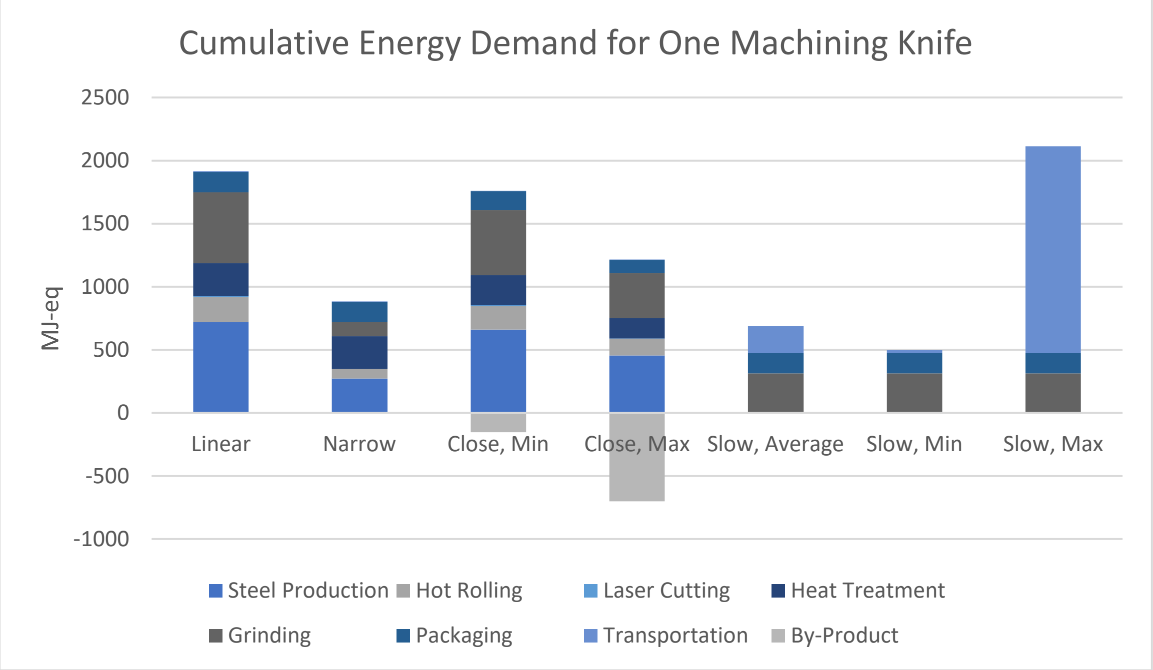

Fig. 4 Cumulative Energy Demand of different Production Cases.

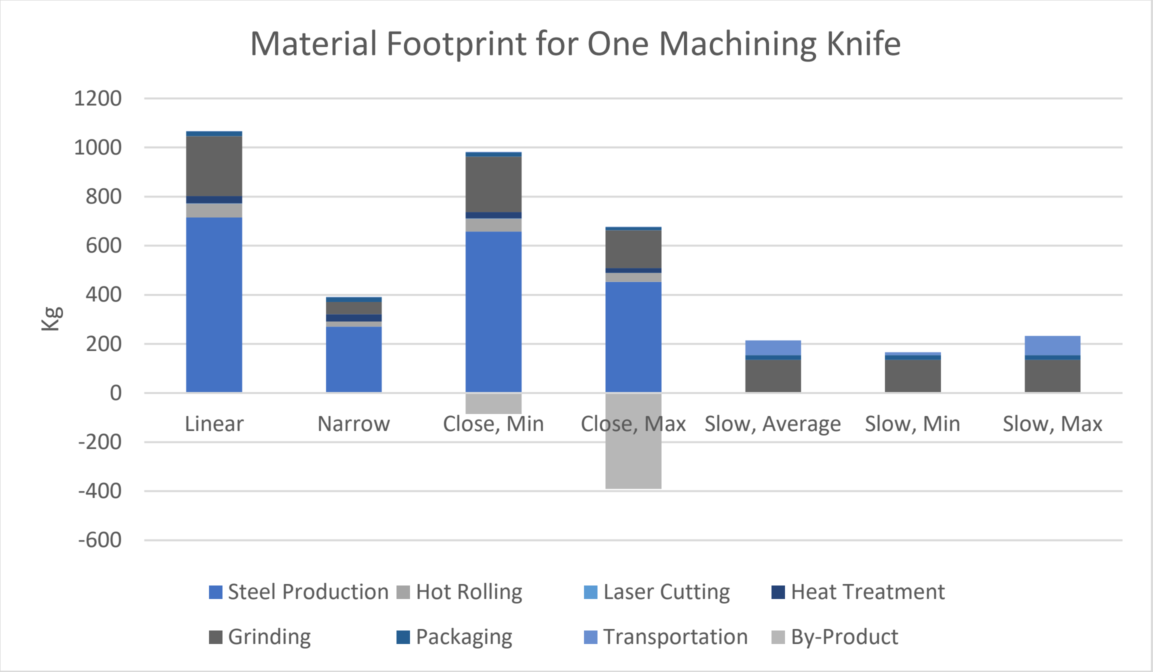

Fig. 5 Material Footprint of different Production Cases.

Tab. 3 Environmental Analysis of one Machining Knife for the different Production Cases

	CF	**ΔCF**	**CED**	**ΔCED**	**MF**	**ΔMF**	**Material Efficiency**
Case	**kg CO_2 eq**	**%**	**MJ-eq**	**%**	**kg**	**%**	**%**
Linear	106	0	1915.2	0	1067.6	0	12.5
Narrow	45.4	-57.1	884.2	-53.8	391.4	-63.3	44.1
Close$_{Min}$	97.5	-8	1767	-8	982.2	-8	13.6
Close$_{Max}$	67.2	-36.6	1214.8	-36.6	677.2	-36.6	17.8
Slow$_{Av}$	36.9	-65.2	688.8	-64	213.8	-80	40.4
Slow$_{Min}$	24.3	-77.1	498.4	-74	165.6	-84.5	40.4
Slow$_{Max}$	131.6	+24.2	2113.4	-10.4	232.6	-78.2	40.4

3.5 Sensitivity Analysis

3.5.1 Steel Production

The steel production and the processing of the semi-product were tested. According to the information about the case study, the steel production results in a CF of 0.8 kg CO2 eq, an MF of 13.2 kg, and a CED of 13.3 MJ-eq. In comparison, another database publishes that recycling one kg of steel causes 1-1.1 kg CO_2 eq and demands 12.6-13.9 MJ eq on average, which is slightly higher than the case study results (Granta Design, 2017). According to the published results of the regular global data survey of the worldsteel association, one kg crude steel cast production caused 1.9 kg CO_2 eq and required 20.6 MJ eq in 2020, which is higher than the results in this study (worldsteel, 2021). The share of secondary material is an average value, which is lower, i.e., 37% (worldsteel, 2019b), than the here assumed 95%.

As the calculations in this study differ from the literature, the share of secondary material and chosen energy mix were tested. The results show that changing the energy mix from Germany to global increases all three categories. Further, the higher the share of secondary material, the lower the CF and energy demand. Including the assumptions of the worldsteel association (global energy mix, 37% secondary route (EAF)) the calculations show a convergence: The production of 1 kg steel (AISI D2) causes 1.6 kg CO_2 eq and requires 20.6 MJ eq, which is comparable to the mentioned values from literature (Granta Design, 2017; worldsteel, 2021).

3.5.2 Individual Energy Mix

The environmental analysis for the processes at the manufacturer's production site, heat treatment, and grinding includes an adapted energy mix. The impact of conventional production is compared to the production based on the average German, European, and global energy mix. The adapted energy mix causes the lowest environmental impact, which is shown by the results in Tab. 4. An exception is the CF, which continues to decrease using the European energy mix. It can be attributed to the low share of fossil energy sources. In contrast, a higher share of nuclear energy offsets this. The global energy mix has the highest impact in all three categories because of the highest share of fossil energy. Generally, the choice of the energy mix significantly influences the overall impact of the cradle-to-gate production of one machining knife.

Tab. 4 Influence of the Energy Mix for the Heat Treatment and Grinding process according to Case A[1]

	CF	**Δ total CF**	**CED**	**Δ total CED**	**MF**	**Δ total MF**
	kg CO_2 eq	**%**	**MJ-eq**	**%**	**kg**	**%**
Individual	46.9	0.0	787.0	0.0	269.4	0.0
Germany	55.6	8.2	915.6	6.7	283.8	1.4
Europe	44.1	-2.7	950.6	8.5	267.7	0.2
Global	61.1	13.4	973.7	9.8	285.2	1.5

---

[1] The results show the impact for the heat treatment and grinding processes, which take place at the production plant of the producer. The producer uses an energy mix with a higher share of renewable energy. The “Individual” energy mix represents the reference process. It is compared to the impact of the processes based on varying average energy mixes provided by ecoinvent – Germany, Europe, Global.

3.5.3 Transportation

The transportation is relevant for remanufacturing (Slow) as larger machining knives at the EoL are the material input and must be returned from the first customer. As the products are sold worldwide, the distance and the transport modes vary greatly. Based on the data provided by the manufacturer, possible transport routes were defined and calculated. The results show the high variance of the impact of transportation as Tab. 5 shows. The environmental impact of transportation can potentially offset the savings from the CF and CED. This applies to the maximum distance considering air freight. The other transport routes only reduce the savings for the CF and CED. The MF also varies, but it has a low influence on the overall savings. The MF is the highest for intra-European transportation due to the high share of transport via road, including material demand for road construction. The results show that the global transport routes have average lower CF, CED, and MF. The reason is the high share of sea freight with a lower impact.

Tab. 5 Influence of the Transportation for returning the Machining Knives at EoL according to Case D[2]

	CF kg CO_2 eq	Share of total CF %	CED MJ-eq	Share of total CED %	MF kg	Share of total MF %
Minimum	1.5	6.2	23.7	4.8	11.3	6.8
Average Europe	21.5	48.5	349.2	42.4	166.1	51.8
Average Global	14.0	38.0	214.0	31.1	59.4	27.7
Maximum excl. air	9.5	29.4	139.2	22.7	39.1	20.2
Maximum incl. air	108.7	82.7	1638.7	77.5	78.2	33.6

4 Discussion

The case study compares the linear production of a machining knife (Linear) to production scenarios (Narrow, Close, Slow) adapted according to the CE, which aim to achieve increased material efficiency.

The reasonably low material efficiency of the linear machining knife of 12.5% (Linear) can be increased by 1.1%-5.3% (Close), 27.9% (Slow), or even 31.6% (Narrow). The scenarios thus work towards the goal of the CE to increase material efficiency by reducing, alternatively reusing, recycling, and recovering materials along the value chain (Kirchherr et al., 2017). The environmental analysis also confirms often presumed environmental benefits, which is valid for all three adapted production processes (Narrow, Close, Slow) compared to the conventional production process (Linear). The most significant improvement of environmental performance concerning the CF, CED, and MF is achieved by remanufacturing (Slow), followed by the adapted production of semi-product (Narrow) and using the grinding sludge (Close). The results show that the change in material efficiency does not correlate with the change in environmental impact. Whereas the Case of narrowing has the highest material efficiency, the Case of slowing has the lowest CF, CED and MF on average.

---

[2] The table shows the environmental impact related to different transport scenarios for the return of one larger machining knife at its EoL as the input for the remanufacturing. The *minimum* scenario represents the customer with the lowest distance and transportation via truck. The *average Europe* and *Global* considers the average distance and transport route to European and global customers. The former happens mostly via truck. The latter includes all transport modes. The *maximum* scenario represents the transportation to the farest customer, which can occur mainly via sea freight (*excl. air*) or via cargo flight (*incl. air*). The share refers to the impact of one remanufactured machining knife.

The comparison of the case study to further literature is only possible to a limited extent, which relates to the environmental impact of the machining knife and the application of the CE strategies. The studies in the context of steel still strongly focus on steel production and recycling (Branca et al., 2020; Haupt et al., 2017). In this context, the literature offers studies focusing on single technologies for steel processing, which are considered in the calculations (Azevedo et al., 2018; Linke and Overcash, 2012; Silva et al., 2015). Some studies focus on the reuse of trusses and material efficiency strategies in the entire steel industry (Brütting et al., 2019; Milford et al., 2013). However, both cited studies are not comparable because of the different fields of application and scope. Thus, there is a lack of case studies focusing on steel products and the application of CE strategies allowing a comparison of the results. This is also noticeable in the literature regarding metalworking processes such as ring rolling and PM processes (Allwood et al., 2005; Azevedo et al., 2018). The data availability for modelling and comparison is limited.

To address further insecurities, assumptions for the conventional production (Linear) are challenged by the testing of the steel production in Chapter 3.5.1 and energy mix in Chapter 3.5.2. The CF of the crude steel is comparably low due to the German energy mix and high scrap share, which results from the high scrap share of the steel. The adaption of the energy mix according to the individual energy composition of the manufacturer lowers the impact of the resource- and energy-intensive processes like heat treatment and grinding.

The influence of the varying transportation of returning the machining knives in the case of remanufacturing (Slow) was also tested as illustrated in Chapter 3.5.3. It can compensate the environmental savings regarding the CF. That is the case of the maximum distance and including air freight. This combination of distance and type of transportation is used within time-critical deliveries. It can be avoided by proper resource planning. Also, it shows that implementing CE is not necessarily environmentally beneficial. Changes in auxiliary processes like transportation can be significant and should be considered when evaluating a circular product system.

Regarding transportation, it can be argued that metal scrap is traded globally. Therefore, it is transported anyway, which can significantly influence embodied energy and GHG emissions (Chong and Hermreck, 2011). Especially as Germany is one leader in the network of steel trading (Hu et al., 2020). Nevertheless, the transportation of the machining knives differs from scrap as they are packed in robust and heavy packaging, increasing the transportation weight. Also, the density of the packed knife at the EoL is likely reduced due to how they are fixed. The transport is done in small batches, rather than parcels, than in large containers resulting in the integration of smaller lorries in the transportation system. Thus, fuel consumption and the related environmental intensities are higher.

Regarding the methodology, the LCA is restricted to CF, CED, MF, and material efficiency. The choice of indicators is built upon the knowledge that the steel industry is carbon- and energy-intensive and that metalworking processes are resource-intensive (Linke and Overcash, 2012; Silva et al., 2015). The material efficiency indicator was chosen to assess the overarching goal of the CE. The case study shows the limit of only focusing on material efficiency and mass-based indicators, which is already shown by other studies (Elia et al., 2017; Harris et al., 2021; Saidani et al., 2019). Material efficiency considers the material inputs for the main product, which leads to the exclusion of processes such as transportation (Reinhart et al., 2011). This results e. g. in the constant material efficiency for the Slowing Case by varying environmental impacts. This result shows that material efficiency as a proxy for environmental benefits is not necessarily conclusive. Further, the material efficiency indicator does not correlate with the environmental impacts.

Another aspect to consider is the focus of the MF on the input side. It reflects the reduced amount of crude steel and grinding process properly. Conversely, the variation of e. g. carbon-intensive processes such as the transportation route is comparably low. The same applies to the CED, which is still more sensitive than the MF. It clearly illustrates the importance of including environmental impact categories focusing on the output side rather than on only material inputs.

The implementation of circular concepts with a higher degree of circularity than recycling and recovery faces the latter's limits. So far, recycling has achieved a significant reduction in environmental impact. Steel production via the secondary route (EAF) causes fewer GHG emissions than the primary route (BOF). As calculated, the global production of 1 kg of AISI D2 causes 0.8 kg CO_2 eq via the secondary route and 2 kg CO_2 eq via the primary route (see SI). Steel is often claimed to be indefinitely reusable. It is theoretically true, but it faces many limits in practice. During the recycling process, some of the smelt is lost to the slag. This affects rather the minor and often critical alloying elements than the major metal Fe (Graedel et al., 2022). As the recycling system is not 100% efficient, the steel is contaminated by unwanted tramp elements, which can affect the material properties. In the case of copper, it can cause the cracking of the surface in forming processes when it is above a concentration of 0.1 wt% (Daehn et al., 2017). This loss in functionality is called downcycling and requires a dilution by adding primary material to lower the concentration of copper (Daehn et al., 2017; Helbig et al., 2022). It would require a perfect sorting of the thousands of steel types to avoid these effects, which is practically not feasible (Graedel et al., 2022). It would require steel scrap within certain qualities defined by tolerance levels. These are available, but only to a limited extent (Dworak and Fellner, 2021). Not considering such fundamental knowledge in the theoretical foundations of the CE, its goals seem "over-simplistic" and might lead to unintended consequences (Murray et al., 2012). Therefore, the focus should be on quality aspects, i.e., considering downcycling and upcycling rather than quantities only (Cullen, 2017; Daehn et al., 2017). By reusing the steel as shown in this case study (Close, Slow), the information regarding the specific steel alloy and its material characteristics are known, and the functionalities are considered for the second application. Reusing the steel before a second smelting process also avoids energy- and thus carbon-intensive production steps such as the necessary heat treatment, which is required to achieve certain material characteristics.

The case study considers the three approaches to increase material efficiency and decrease environmental impact separately. Ideally, the three scenarios could be integrated, starting with producing the larger machining knife by ring rolling (Narrow). The larger machining knife at its EoL is the input for producing the smaller one (Slow), avoiding crude steel production and reducing the amount of grinding sludge. Then, the grinding sludge can be returned to value-adding cycles (Close). Such combinations and extensions should be part of further investigations. The repurpose strategy could be value-adding as well when considering the smallest machining knife at its EoL. It could be used for producing smaller products requiring similar material properties such as blades.

The transferability of the case study throughout the worldwide steel industry is also given. In terms of narrowing, the focus should be on processing semi-products rather than on semi-products themselves. The latter already have high production yields above 90% (Cullen et al., 2012). One exception is the casting of intermediate products. To further increase production yields while using separating production processes, the approach of intelligent nesting or alternative production routes can be helpful.

Also, the treatment of grinding sludge (Closing) has great potential as it is a waste stream resulting from various metal cutting processes like drilling, grinding, turning, sawing, and honing (Abdelrazek et al., 2020; Silva et al., 2015). The sludge contains metal chips, cutting fluid, and abrasives. As all three inputs can vary in the specific material input, there is a diversity of sludges. The approach of separating the individual components in order to be able to reuse the high-quality materials individually for demanding applications has been tried and tested in the steel sector (Hankel et al., 2020; Jäger et al., 2021). However, the approach can also be applied to metallic abrasive slurries in general. For example, there are promising approaches and research in the field of NeFeB magnets (Raulf and Pretz, 2017). Considering the measured yields within the cutting processes of the exemplary intermediate products as listed in Fig. 2, the potentially low production yields in the metalworking industry become clear. The apparent steel use was 35.2 Mt in Germany and 147 Mt in Europe in 2021, with the share of final use for metal goods of 14% (Eurofer, 2022; worldsteel, 2022). Even without exact data for the steel industry, the enormous potential becomes apparent. Considering the German metalworking industry without the limitation on steel, 1.5 Mt of metal chips and 280 kt of grinding sludge arise annually, which commonly end up in the cement industry (Reschke et al., 2019). It has low qualitative requirements, and the functionalities of the valuable metals are dissipatively lost.

Regarding the strategy of reusing the steel product (Slowing), the transferability is also given, as shown by other publications (Brütting et al., 2019; Milford et al., 2013). The product is made from steel only and is close to the shape of a sheet. There is another case study applying the case of reusing a steel product with low complexity in terms of material diversity and the usage of flat parts (Brütting et al., 2019). Also, the second product life addresses similar functionality as the first product life, which is also given in this case study. The geometry and functionality are exclusion criteria. The transfer of the reusing of products in terms of reworking should be further investigated. Especially regarding the diversity of materials and components, quality control, and the combination of suitable initial and target products. So far, no specific findings are known about which product group or sectors are particularly suitable for for implementation.

5 Conclusion

The investigated case study of an industrial machining knife shows the untapped potential of implementing CE strategies beside the established recycling in the metalworking industry. The adaptions developed in research projects cover the three strategies: producing the circular blank close to the counter by radial-axial ring rolling (Narrow), extracting metal chips from the grinding sludge (Close), and using a larger machining knife at its EoL as a material input for the production process (remanufacturing, Slow). The results of the environmental analysis answer the initially stated research questions:

(1) The implementation of the CE leads to an increase of material efficiency and decrease of environmental impact for all interventions compared to conventional production route. The analysis validates the increase in material efficiency, which is the overall aim of the CE. The highest results are achieved by narrowing (44.1%) followed by slowing (40.4%) and closing (13.6-17.8%). The often-presumed environmental benefits related to implementing CE strategies are also confirmed. Adapting the production process according to slowing leads to a reduction of approximately two-third in all covered environmental impact categories. Narrowing the resource flow leads to a comparable result. Using the metal content in the waste stream by grinding sludge and thus closing the resource flow results in the smallest improvement in environmental performance. Depending on the yield, 8-36.6% of the environmental impact of the machining knife can be allocated to the chips, which are a material input in the powder metallurgical process. Considering and implementing the concepts of the CE besides recycling and recovery avoids the latter's limits. The remelting of steel is established and achieved a reduction of the environmental impact of steel production. It is often claimed that steel can be circulated indefinitely. However, it goes along with losses of material and its inherent functionality. It requires alloying elements as primary material and further processing to again achieve the

functionalities. Both go along with high environmental impact. The case study introduces how to implement the CE and with that avoid the remelting and obtain the qualitative value of the high-alloyed steel.

(2) The study shows that the steel production, the energy mix regarding the manufacturing processes and auxiliary processes such as the transportation system significantly influence the environmental performance. It is important to consider auxiliary processes such as transportation as they have the potential to compensate the environmental savings.

(3) The assessment also stresses the differences between the included environmental impact categories as well as the limits of input and mass-based indicators. This result becomes clear when evaluating the transportation for returning the products for remanufacturing. The MF and CED have significantly lower sensitivity than the CF. The choice of indicators and environmental impact categories should be made carefully. Also, the material efficiency as an indicator does not correlate with the impacts resulting from the Life Cycle Assessment.

The case study presented shows the enormous potential of implementing CE concepts in the metalworking industry. To consolidate appropriate assessment approaches and holistically recognize the opportunities of the CE, further case studies are needed to collect data and insights.

CRediT

Wiebke Hagedorn: Conceptualization, Methodology, Investigation, Writing, Formal Analysis; **Sebastian Jäger:** Writing, Investigation; **Lucas Wieczorek:** Writing, Investigation; **Philipp Kronenberg:** Writing, Investigation; **Kathrin Greiff:** Supervision; **Sebastian Weber:** Supervision, **Arne Röttger:** Supervision.

Acknowledgments

Funding: This work was supported by the Regional Development, the promoter Leitmarktagentur NRW and the promoter ETN regarding the projects EffProSchliffUp[EFRE-0801163] and EffProRonde [EFRE-0801519] as well as by the

German Ministry of Education and Research regarding the project Circle of Tools [033R230F].

Furthermore, the authors would like to thank the consortium management of the projects and for the provision of the source material, which enables the scientific research within this project.

Data Statement

Due to the sensitive nature of the questions asked in this study, not all primary data from the production processes are disclosed as it should remain confidential.

References

Abdelrazek, A.H., Choudhury, I.A., Nukman, Y., Kazi, S.N., 2020. Metal cutting lubricants and cutting tools: a review on the performance improvement and sustainability assessment. Int. J. Adv. Manuf. Technol. 106, 4221–4245. https://doi.org/10.1007/s00170-019-04890-w

Allwood, J.M., Ashby, M.F., Gutowski, T.G., Worrell, E., 2011. Material efficiency: A white paper. Resour. Conserv. Recycl. 55, 362–381. https://doi.org/10.1016/j.resconrec.2010.11.002

Allwood, J.M., Tekkaya, A.E., Stanistreet, T.F., 2005. The Development of Ring Rolling Technology. Steel Res. Int. 76, 111–120. https://doi.org/10.1002/srin.200505981

Azevedo, J.M.C., CabreraSerrenho, A., Allwood, J.M., 2018. Energy and material efficiency of steel powder metallurgy. Powder Technol. 328, 329–336. https://doi.org/10.1016/j.powtec.2018.01.009

Baracchini, G., Bianco, L., Cirilli, F., Echterhof, T., Griessacher, T., Marcos, M., Mirabile, D., Reichel, T., Rekersdrees, T., Sommerauer, H., European Commission, Directorate-General for Research and Innovation, 2018. Biochar for a sustainable EAF steel production (GREENEAF2): final report.

Bargel, H.-J., Schulze, G. (Eds.), 2012. Werkstoffkunde: jetzt mit Aufgaben und Lösungen, 11., bearb. Aufl. ed, Springer-Lehrbuch. Springer Vieweg, Berlin.

Berns, H., 1977. Kaltarbeitsstähle für Schneidwerkzeuge. Werkst. Gebräuchlichen Stähle 2, 205–213.

Beylot, A., Ardente, F., Sala, S., Zampori, L., 2021. Mineral resource dissipation in life cycle inventories. Int. J. Life Cycle Assess. https://doi.org/10.1007/s11367-021-01875-4

Bocken, N.M.P., Pauw, I., Bakker, C., van der Grinten, B., 2016. Product Design and Business Model Strategies for a Circular Economy. J. Ind. Prod. Eng. 33, 308–320. https://doi.org/10.1080/21681015.2016.1172124

Branca, T.A., Colla, V., Algermissen, D., Granbom, H., Martini, U., Morillon, A., Pietruck, R., Rosendahl, S., 2020. Reuse and Recycling of By-Products in the Steel Sector: Recent Achievements Paving the Way to Circular Economy and Industrial Symbiosis in Europe. Metals 10, 345. https://doi.org/10.3390/met10030345

Brinksmeier, E., Eckebrecht, J., Buhr, H., 1994. Improving ecological aspects of the grinding process by effective waste management. J. Mater. Process. Technol. 44, 171–178. https://doi.org/10.1016/0924-0136(94)90429-4

Brinksmeier, E., Meyer, L., Walter, A., Wittmann, M., 2001. Schleifprozesse verbessern: Optimierter Einsatz von Kühlschmierstoffen. ZWF Z. Für Wirtsch. Fabr. 96, 453–457. https://doi.org/10.3139/104.100463

Brütting, J., Desruelle, J., Senatore, G., Fivet, C., 2019. Design of Truss Structures Through Reuse. Structures 18, 128–137. https://doi.org/10.1016/j.istruc.2018.11.006

Chong, W.K., Hermreck, C., 2011. Modeling the use of transportation energy for recycling construction steel. Clean Technol. Environ. Policy 13, 317–330. https://doi.org/10.1007/s10098-010-0303-7

Ciroth, A., 2007. ICT for environment in life cycle applications openLCA — A new open source software for life cycle assessment. Int. J. Life Cycle Assess. 12, 209–210. https://doi.org/10.1065/lca2007.06.337

Cullen, J.M., 2017. Circular Economy: Theoretical Benchmark or Perpetual Motion Machine? J. Ind. Ecol. 21, 483–486. https://doi.org/10.1111/jiec.12599

Cullen, J.M., Allwood, J.M., Bambach, M.D., 2012. Mapping the Global Flow of Steel: From Steelmaking to End-Use Goods. Environ. Sci. Technol. 46, 13048–13055. https://doi.org/10.1021/es302433p

Daehn, K.E., Cabrera Serrenho, A., Allwood, J.M., 2017. How Will Copper Contamination Constrain Future Global Steel Recycling? Environ. Sci. Technol. 51, 6599–6606. https://doi.org/10.1021/acs.est.7b00997

Dworak, S., Fellner, J., 2021. Steel scrap generation in the EU-28 since 1946 – Sources and composition. Resour. Conserv. Recycl. 173, 105692. https://doi.org/10.1016/j.resconrec.2021.105692

Elia, V., Gnoni, M.G., Tornese, F., 2017. Measuring Circular Economy Strategies through Index Methods: A Critical Analysis. J. Clean. Prod. 142, 2741–2751. https://doi.org/10.1016/j.jclepro.2016.10.196

EN ISO, 2020a. Environmental Management - Life Cycle Assessment - Principles and Framework. ISO 14040:2006 + Amd 1:2020.

EN ISO, 2020b. Environmental Management - Life Cycle Assessment - Requirements and Guidelines. ISO 14044:2006 + Amd 1:2017 + Amd 2:2020.

Eurofer (Ed.), 2022. Economic and Steel Market Outlook 2022-2023. Eurofer, Brussel.

Flint, I.P., Cabrera Serrenho, A., Lupton, R.C., Allwood, J.M., 2020. Material Flow

Analysis with Multiple Material Characteristics to Assess the Potential for Flat Steel Prompt Scrap Prevention and Diversion without Remelting. Environ. Sci. Technol. 54, 2459–2466. https://doi.org/10.1021/acs.est.9b03955

Graedel, T.E., Reck, B.K., Miatto, A., 2022. Alloy information helps prioritize material criticality lists. Nat. Commun. 13, 150. https://doi.org/10.1038/s41467-021-27829-w

Granta Design, 2017. CES Selector 2017 (Material Database). Granta Design Ltd.

Hagedorn, W., Greiff, K., Liedtke, C., 2020. The Environmental Impact of Steel Tools designed for Re-Manufacturing and Re-purposing. Presented at the Life Cycle Innovation Conference 2020, FSLCI, Berlin.

Hankel, J., Jäger, S., Weber, S., 2020. Development of a recycling strategy for grinding sludge using supersolidus liquid phase sintering. J. Clean. Prod. 263, 121501. https://doi.org/10.1016/j.jclepro.2020.121501

Harris, S., Martin, M., Diener, D., 2021. Circularity for circularity's sake? Scoping review of assessment methods for environmental performance in the circular economy. Sustain. Prod. Consum. 26, 172–186. https://doi.org/10.1016/j.spc.2020.09.018

Haupt, M., Vadenbo, C., Zeltner, C., Hellweg, S., 2017. Influence of Input-Scrap Quality on the Environmental Impact of Secondary Steel Production: Influence of Scrap Quality on EAF Steel Production. J. Ind. Ecol. 21, 391–401. https://doi.org/10.1111/jiec.12439

Hauschild, M.Z., Rosenbaum, R.K., Olsen, S.I. (Eds.), 2018. Life Cycle Assessment. Springer International Publishing, Cham. https://doi.org/10.1007/978-3-319-56475-3

Helbig, C., Huether, J., Joachimsthaler, C., Lehmann, C., Raatz, S., Thorenz, A., Faulstich, M., Tuma, A., 2022. A terminology for downcycling. J. Ind. Ecol. 1–11.

Hu, X., Wang, C., Lim, M.K., Koh, S.C.L., 2020. Characteristics and community evolution patterns of the international scrap metal trade. J. Clean. Prod. 243, 118576. https://doi.org/10.1016/j.jclepro.2019.118576

Ito, A., Langefeld, B., Götz, N., Lecat, A., Hayes, G., Chen, Y., 2020. The Future of Steelmaking - How the European Steel Indsutry can achieve Carbon Neutrality, Focus. Roland Berger, München.

Jäger, S., Weber, S., Röttger, A., 2021. Potential of the Recycling of Grinding Sludge by various Powder Metallurgical Processes. Procedia CIRP 104, 893–899.

Kirchherr, J., Reike, D., Hekkert, M., 2017. Conceptualizing the Circular Economy: An Analysis of 114 Definitions. Resour. Conserv. Recycl. 127, 221–232. https://doi.org/10.1016/j.resconrec.2017.09.005

Kronenberg, P., Wieczorek, L., Weber, S., Röttger, A., 2022. Quantification of methods used in field metallography using the example of quality assurance measures for a circular economy for high-alloy steels. Pract. Metallogr. 59, 296–316. https://doi.org/10.1515/pm-2022-0034

Li, X., Sun, W., Zhao, L., Cai, J., 2018. Material Metabolism and Environmental Emissions of BF-BOF and EAF Steel Production Routes. Miner. Process. Extr. Metall. Rev. 39, 50–58. https://doi.org/10.1080/08827508.2017.1324440

Liedtke, C., Bienge, K., Wiesen, K., Teubler, J., Greiff, K., Lettenmeier, M., Rohn, H., 2014. Resource Use in the Production and Consumption System—The MIPS Approach. Resources 3, 544–574. https://doi.org/10.3390/resources3030544

Linke, B., Overcash, M., 2012. Life Cycle Analysis of Grinding, in: Dornfeld, D.A., Linke, B.S. (Eds.), Leveraging Technology for a Sustainable World. Springer Berlin Heidelberg, Berlin, Heidelberg, pp. 293–298. https://doi.org/10.1007/978-3-642-29069-5_50

Lohmar, J., Cleaver, C.J., Allwood, J.M., 2020. The influence of constraint rolls on temperature evolution and distribution in radial ring rolling. J. Mater. Process. Technol. 282, 116663. https://doi.org/10.1016/j.jmatprotec.2020.116663

Milford, R.L., Pauliuk, S., Allwood, J.M., Müller, D.B., 2013. The Roles of Energy and Material Efficiency in Meeting Steel Industry CO $_2$ Targets. Environ. Sci. Technol. 47, 3455–3462. https://doi.org/10.1021/es3031424

Murray, V.R., Zhao, F., Sutherland, J.W., 2012. Life cycle analysis of grinding: a case study of non-cylindrical computer numerical control grinding via a unit-process life cycle inventory approach. Proc. Inst. Mech. Eng. Part B J. Eng. Manuf. 226, 1604–1611. https://doi.org/10.1177/0954405412454102

Oppenkowski, A., 2011. Cryobehandlung von Werkzeugstahl. RUB, Lehrstuhl Werkstofftechnik, Bochum.

Pauliuk, S., Heeren, N., 2020. Material efficiency and its contribution to climate change mitigation in Germany : A deep decarbonization scenario analysis until 2060. J. Ind. Ecol. jiec.13091. https://doi.org/10.1111/jiec.13091

Pauliuk, S., Wang, T., Müller, D.B., 2013. Steel all over the world: Estimating in-use stocks of iron for 200 countries. Resour. Conserv. Recycl. 71, 22–30. https://doi.org/10.1016/j.resconrec.2012.11.008

Potting, J., Hekkert, M., Worrell, E., Hanemaaijer, A., 2017. Circular Economy: Measuring Innovation in the Product Chain.

Raimondi, A., Girotti, G., Blengini, G.A., Fino, D., 2012. LCA of petroleum-based lubricants: state of art and inclusion of additives. Int. J. Life Cycle Assess. 17, 987–996. https://doi.org/10.1007/s11367-012-0437-4

Raulf, K., Pretz, T., 2017. Model-Based Comparison of Recycling Processes for Grinding Slurries from NdFeB-Magnet Production. J. Sustain. Metall. 3, 150–167.

Reinhart, G., Reinhardt, S., Föckerer, T., Zäh, M.F., 2011. Comparison of the Resource Efficiency of Alternative Process Chains for Surface Hardening, in: Hesselbach, J., Herrmann, C. (Eds.), Glocalized Solutions for Sustainability in Manufacturing. Springer Berlin Heidelberg, Berlin, Heidelberg, pp. 311–316. https://doi.org/10.1007/978-3-642-19692-8_54

Reschke, C., Schubert, D., Biedermann, H., Deike, R., 2019. Verfahren zur Entölung von kühlschmierstoffbehafteten Metallspänen und -schlämmen, in: Recycling Und Rohstoffe. Thomé-Kozmiensky Verlag GmbH, Neuruppin.

Rostek, L., Lotz, M.T., Wittig, S., Herbst, A., Loibl, A., Espinoza, L.T., 2022. A dynamic material flow model for the European steel cycle (No. S07/2022), Working Paper Sustainability and Innovation. ZBW, Fraunhofer Institut für System- und Innovationsforschung ISI, Karlsruhe.

Saidani, M., Yannou, B., Leroy, Y., Cluzel, F., Kendall, A., 2019. A Taxonomy of Circular Economy Indicators. J. Clean. Prod. 207, 542–559. https://doi.org/10.1016/j.jclepro.2018.10.014

Saurat, M., Ritthoff, M., 2013. Calculating MIPS 2.0. Resources 2, 581–607. https://doi.org/10.3390/resources2040581

Silva, D.A.L., Filleti, R.A.P., Christoforo, A.L., Silva, E.J., Ometto, A.R., 2015. Application of Life Cycle Assessment (LCA) and Design of Experiments (DOE) to the Monitoring and Control of a Grinding Process. Procedia CIRP 29, 508–513. https://doi.org/10.1016/j.procir.2015.01.037

Teubler, J., Weber, S., Suski, P., Peschke, I., Liedtke, C., 2019. Critical evaluation of the material characteristics and environmental potential of laser beam melting processes for the additive manufacturing of metallic components. J. Clean. Prod. 237, 117775. https://doi.org/10.1016/j.jclepro.2019.117775

TKM, 2022. Photograph of Log Saw. Personal Communication.

UNEP, 2021. Emissions Gap Report 2021. The Heat is On - A World of Climate Promises Not Yet Delivered. United Nations Environment Programme; International Resource Panel, Nairobi, Kenya.

UNEP (Ed.), 2013. Metal recycling: opportunities, limits, infrastructure: this is report 2b of the Global Metal Flows Working Group of the International Resource Panel of UNEP. United Nations Environment Programme, Nairobi, Kenya.

Wernet, G., Bauer, C., Steubing, B., Reinhard, J., Moreno-Ruiz, E., Weidema, B., 2016. The ecoinvent database version 3 (part I): overview and methodology. Int. J. Life Cycle Assess. 21, 1218–1230. https://doi.org/10.1007/s11367-016-1087-8

Wiesen, K., Saurat, M., Lettenmeier, M., 2014. Calculating the Material Input per Service Unit using the Ecoinvent database. Int. J. Perform. Eng. 10, 357–366.

worldsteel (Ed.), 2022. World Steel in Figures 2022.

worldsteel (Ed.), 2021. Steel and Raw Materials. Factsheet.

worldsteel, 2019a. Steel Statistical Yearbook 2019. Concise Version. Worldsteel Association, Brussel.

worldsteel, 2019b. Sustainable steel indicators 2019 and the steel supply chain. Worldsteel Assoc.

WV Stahl, 2020. Fakten zur Stahlindustrie in Deutschland 2020.

Xylia, M., Silveira, S., Duerinck, J., Meinke-Hubeny, F., 2018. Weighing regional scrap availability in global pathways for steel production processes. Energy Effic. 11, 1135–1159. https://doi.org/10.1007/s12053-017-9583-7