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An appraisal of the cradle-to-gate energy demand and carbon footprint of high-speed steel cutting tools

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Abstract

The awareness of the environmental impact of the manufacturing sector has increased over the last few decades. This paper presents the results of an LCA-based approach used to evaluate the production of a threading tool (i.e., an M10 × 1.25 spiral point tap) made of high-speed steel. The cumulative energy demand and CO_2-equivalent emissions have been quantified throughout the entire tool manufacturing process. Both the pre-manufacturing steps and the upstream/downstream flows of the used material have been accounted for, considering cradle-to-gate (plus end-of-life) system boundaries. The results show that the share of primary energy employed to produce the tool is mainly imputable to the manufacturing processes. Therefore, this analysis could contribute to fostering the development of structured assessment frameworks that would allow cutting tool manufacturers to identify the weak points of their production routes to be optimized.

Keywords: Sustainable manufacturing; Machining; Cutting tool; Energy consumption; Carbon Dioxide Emissions.

1. Introduction

The current growing interest in environmental sustainability, linked to the themes of global warming and resource depletion, has had repercussions on all industrial sectors, and is playing an increasingly important role in both decision-making and marketing. Different opportunities for sustainable manufacturing in the macro-perspective of Industry 4.0 can be highlighted [1], and different solutions have to be implemented to minimize the consumption of materials, resources, and energy, as well as the release of carbon dioxide and other greenhouse gases (GHGs). Manufacturing is usually characterized by a high degree of energy consumption and use of consumable resources, and this leads to an overall high impact on the environment (as recently reported by ISPRA [2] for the Italian manufacturing industry). Even though the GHG emission trend has shown a decrease in the last few years, e.g., due to an ever-greater use of greener energy mixes, further steps are needed to reach the climate-neutrality targets [3]. It has therefore become important to perform analyses of the industrial production sector to optimize both products and processes, considering all the economic, environmental and social aspects whenever possible.

1.1. Sustainability of machining and the role of cutting tools

Several efforts have been made over the last decade to account for sustainability issues resulting from machining operations, whereby the energy consumption and the related CO_2 emissions have been assessed and/or predicted. The literature highlights that there is a need for such analyses to be

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executed holistically at the system level [4], that is, they should include all the contributions related to consumables, such as the impact embodied in the cutting fluid(s) and tool(s) [5, 6]. However, as far as the latter is concerned, only a few research studies have included and/or addressed the environmental impact of cutting tools. Among others, Liu et al. [7] quantified the embodied energy of tools used for milling and underlined the importance of considering the impact of both the cutting tools and the processed material when evaluating the total energy consumption, as well as the energy required by the machine. Kirsch et al. [8] conducted a comparison of different material removal methods (milling and grinding) and analyzed the impact of the production steps of a coated milling tool and of a corundum grinding wheel. They also evaluated the energy incorporated in the materials for each possible scenario, considering both the mixture of the different grains the tools were made of and the binding materials. Li et al. [9] examined the environmental impact of gear hobbing tools throughout their entire life cycle, including the use phase and recycling, and quantified the carbon emissions related to the functional tool life. Their study was conducted considering the different surface treatments required to achieve a longer tool life. Although the material extraction and manufacturing phases accounted for a significant portion of emissions, 70-80% of the CO_2 emissions originated from the use phase, due to grinding operations needed during resharpening. In general terms, the evaluation of the environmental impact of cutting tools should account for both the tool manufacturing route and the composition of the material the tools are made of, and/or are coated with. These factors also affect the performance a tool during the use phase; thus, they are expected to impact the sustainability of the entire machining operation [10]. In this context, life cycle inventory data concerning the different kinds of commercially available tools are usually lacking.

1.2. Aim and structure of the paper

The aim of the present research has been to quantify the environmental impact of a threading cutting tool through onsite measurements of the material and energy flows along with its manufacturing steps. A reasonable estimate of the Cumulative Energy Demand (CED) values and of the related CO_2-equivalent emissions can be achieved by including the modeling of the pre-manufacturing phase and of the raw material flows derived from the primary and/or secondary productions. Section 2 proposes the framework that was used for the assessment, while the case study is described in Section 3, which also includes a report on the individual manufacturing operations. All the details concerning the data inventory collection are listed in Section 4, and this is followed by Section 5 and Section 6, which are dedicated to the analysis of the achieved results and the conclusions, respectively.

2. Materials and methods

The production cycle of a threading cutting tool has been investigated. Its impact, in terms of energy consumption and emissions, was assessed within an LCA framework, which included cradle-to-gate impacts and end-of-life recycling options. The boundaries of the study include the raw material production, the pre-manufacturing (i.e., the bar production) and machining steps, as well as the surface and heat treatments (Fig. 1). The functional unit is a single tool. The energy flows and the emissions related to (*i*) the processed material, (*ii*) the electric energy consumption, and (*iii*) the consumable resources (including cutting tools, lubricants and gases) were quantified for each step, as was (*iv*) the process cycle time. A black-box approach was followed, in which the input and output flows were considered, without investigating the process parameters selected for the different unit processes. CED and CO_2-equivalent emissions were considered as evaluation metrics. To sum and compare the energy embodied in the materials with the electric energy needed to process them, the latter was converted back to a fossil-fuel equivalent [11]. The European Environmental Agency (EEA), with regard to the emissions related to the electric energy production, reports the GHG emission intensity of electricity generation as being representative of the kilograms of $CO_{2\,eq}$ emitted for each kWh of electricity produced/consumed [12]. In the present discussion, the cumulative energy demand is provided in MJ oil-equivalent, and the $CO_{2\,eq}$ emissions are quantified in kg. More details on the corresponding conversion coefficients are given in Section 4.1. Different scenarios were considered to model the raw material production. The results accounting for the net benefits, due to either the incoming recycled content or the outgoing recyclable materials, were compared with those obtained when producing the materials from a primary feedstock [13]. All the data concerning manufacturing operations and surface treatments were acquired on-site in the production plant. The electric energy absorbed by the grid was measured by clamping a Fluke 435-II power/energy logger upstream of each machine tool. Other information about the materials and consumables were extracted from either the CES Selector Database [14] or from the most recent literature on this topic.

3. Case study and processing operations

In this section, the production process for an M10 spiral point tap, which is a cutting tool that is employed to thread through holes, is presented (Fig. 1) according to the procedures followed by the UFS Srl company (Sparone, Turin, Italy), whose details are here omitted for confidentiality reasons. The examined tap is made of high-speed steel (HSS) and TiN coated by means of a PVD treatment. The steel is supplied in the form of 3200-mm long, 10.5 mm diameter round bars, from which 28 taps can be obtained. The first machining stage ('OP 1') is performed on a Citizen L20 sliding-head CNC lathe, equipped with an automatic bar loading device. Here, the bars are turned and divided into segments (×28) to obtain the tap bodies, on which a square end is milled to facilitate gripping. The bars are then subjected to a heat treatment ('OP 2'). A centerless grinding of the shank ('OP 3') is performed using a Ghiringhelli machine. The tip of the tap is then processed, via flute grinding ('OP 4'), in a Zaro TG09 machine, which employs two wheels to grind straight and spiral grooves, respectively. Finally, the thread is made on a GBA CNC grinding machine ('OP 5'). Lubricating oil is used during the cutting operations (OPs 1, 3, 4 and 5) to keep the temperature and wheel wear under the pre-set levels.

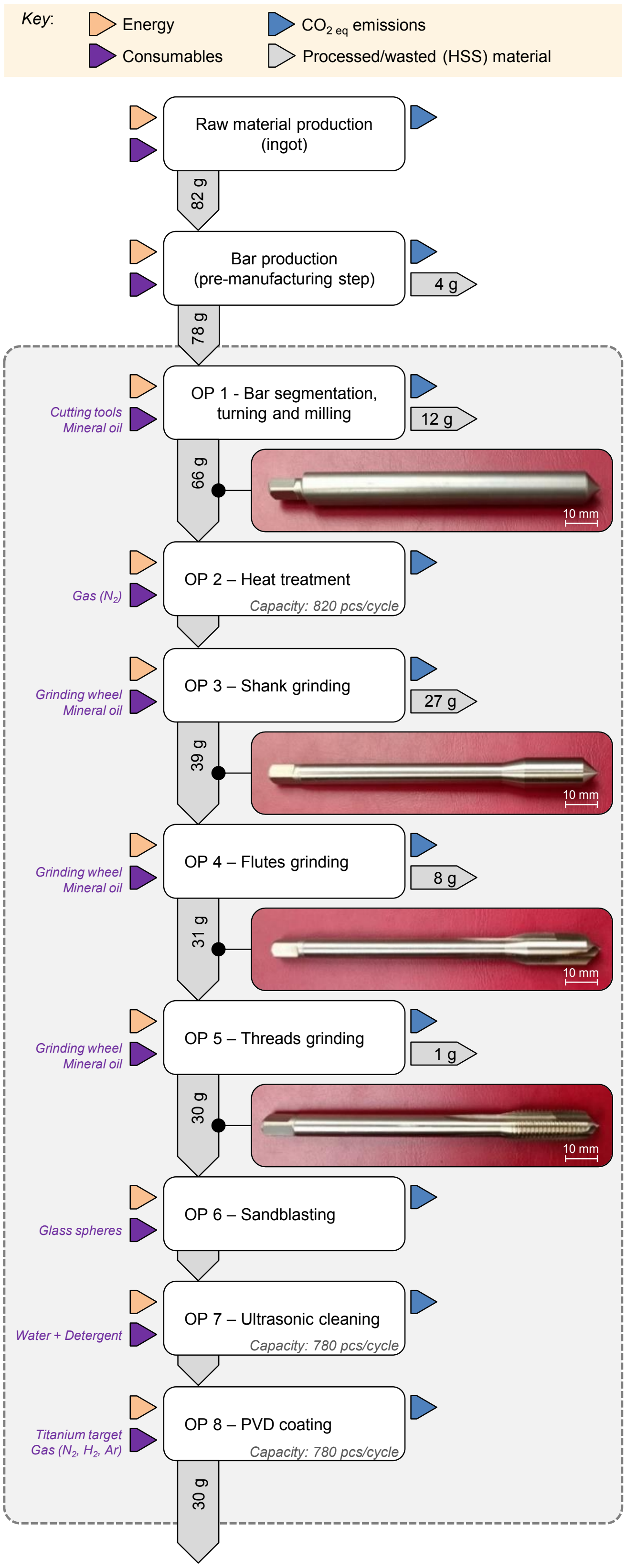

Fig. 1. The different steps of the cradle-to-gate life cycle for the processing of a single M10 spiral point tap, with details on the material, consumables and energy flows, and on the emissions.

In order to remove any burrs that could be generated during grinding, a finishing operation is carried out with a sandblasting machine, using 70÷110-µm diameter glass spheres ('OP 6'). The tap is further treated, by means of ultrasonic cleaning ('OP 7'), to prepare its surface for the PVD TiN coating ('OP 8') and it is then transferred to an FL850 Hauzer furnace. It should be emphasized that, although the process described here is specific for the considered tool, most of these operations are generally adopted for tap manufacturing. Therefore, the methodology can easily be adapted to other, similar case studies.

4. Data inventory

Fig. 1 reports the HSS material flow, in terms of values of the processed and wasted material for each unit process, per functional unit. The 3200-mm long bar, from which 28 taps are machined, weighs approximately 2.2 kg. Therefore, each tap requires 78 g of workpiece. In addition, in order to estimate the raw material consumption, the waste stream from the pre-manufacturing step was accounted for by assuming a yield factor (i.e., the process input/output material ratio) of 1.05 [14]. The embodied energy and CO_2 footprint for the HSS material production, recycling and pre-manufacturing are listed in Table 1. In addition to the average values, a worst- and a best-case scenario (i.e., a range of ± 5 % of the average value, according to [14]), were considered.

Table 1. The eco-properties of the raw material production and pre-manufacturing processes [14].

Process	Energy demand (MJ/kg)	CO_2 emissions (kg/kg)
Primary raw material production	92.6	6.55
Recycling (secondary production)	19.0	1.49
Bar production (pre-manufacturing)	36.5	2.70

Specific information on the production of the incoming feedstock materials is not usually provided by suppliers. When the raw material production is modeled by only assuming the consumption of resources from the primary feedstock, the impact embedded in the material needed to produce a single tap is 7.6 MJ and the CO_2 emissions are equal to 0.54 kg. On the other hand, if the recycled content in the actual material supply is assumed to be as high as 55 % [14], these values (here computed by means of the so-called Recycled Content Approach, RCA [13]) reduce to 4.3 MJ and 0.31 kgCO_2, respectively. Furthermore, the results achieved by applying the Substitution Method (SM) [13], which allocates the full recycling benefits to the end-of-life recyclability (here assumed to be 80 % for both the bulk material and the chips), become 2.8 MJ and 0.20 kgCO_2. Different scenarios are presented later on when discussing the results, as a function of these modeling assumptions. As for the pre-manufacturing step, the contributions for bar production (which should be added to those of the raw material production) are 3.0 MJ and 0.22 kgCO_2.

4.1. Electric energy consumption

The electric energy consumption of each machine tool was acquired in situ. Fig. 2 reports, as an example, the acquisition profile of the required power versus the manufacturing time during the continuous monitoring of OP 1: each peak visible in the signal represents the processing of a single tap. This signal also shows the relatively low levels of energy associated with the downtimes for routine checks/changes of the tools on behalf of the operator, which were amortized equally over the taps produced in the same batch (during the functional unit-related computation).

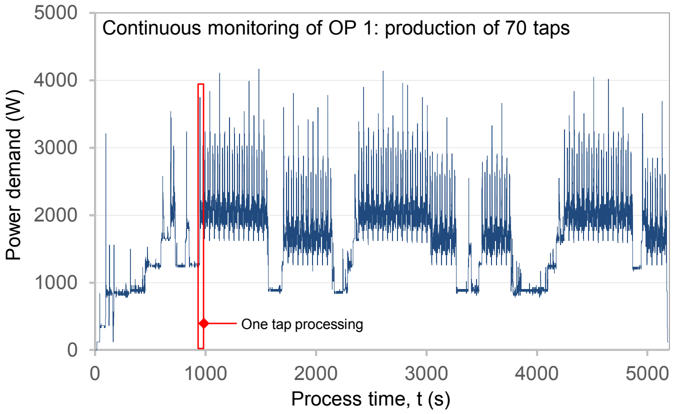

Fig. 2. The power demand versus manufacturing time when monitoring OP 1.

The electric energy consumed for each operation, including both the operational and non-operational times (e.g., the setup) as well as the auxiliary systems (such as the oil filtering equipment and the compressed air generation system, when needed), is summarized in Fig. 3. The overall energy demand for each machine was not analyzed by dividing it into subcategories, as proposed in [15], as this would not have been significant for the present study. The efficiency factor for primary-to-secondary energy conversion was set to 0.38 [11]. An average value of 0.275 $kgCO_2/kWh$, referring to EU-28, was used for the GHG emission intensity. This value is expected to decrease over the years, due to the expected increasing use of greener energy mixes [12].

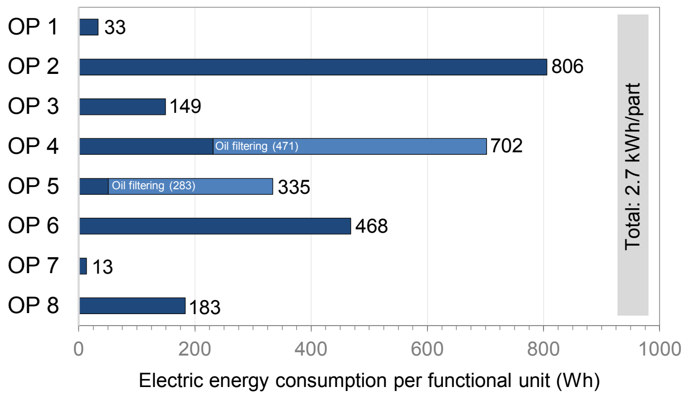

Fig. 3. Summary of the electric energy consumption for each operation.

4.2. Consumables

In addition to electricity consumption, consumables, such as (*i*) the cutting tools and (*ii*) the mineral oil for OPs 1, 3, 4 and 5; (*iii*) the gases used in OPs 2 and 8; (*iv*) the glass spheres employed in the sandblasting operation (OP 6); (*v*) the mixture of water and detergent used for the ultrasonic cleaning operation (OP 7); and (*vi*) the target for PVD coating, should also be considered within the selected boundaries for the analysis. As for the cutting tools, according to Liu et al. [7], the environmental impacts that are embodied in each tool should be divided among the processed components. Dahmus and Gutowski [4] underlined that, although the materials and processes required to manufacture a tool are energy-intensive and the values associated with them are not trivial, if that tool is used in such a way that the energy investment can be distributed over several parts, the energy contribution per part may be assumed as negligible. This is a condition that has actually been observed in the present study, because of the high number of parts produced with the tools per each operation (as detailed in Table 2). Moreover, this is confirmed in the digression that follows. Kirsch et al. [8], when accounting for material production and wheel manufacturing, quantified the embodied energy of a corundum grinding wheel as being 232 MJ. The grinding wheels considered here allow thousands of units to be produced before they need to be substituted. Therefore, if inventory data values that are comparable with (or even greater than) those of Kirsch et al. [8] are assumed, the energy that has to be addressed to the production of a single tap would be of the order of a few tenths of MJ. A similar discussion can be made regarding the cutting tools for turning and milling (OP 1). The center drill was made of HSS, whereas all the inserts were made of coated tungsten carbide. The weight of each tool is less than 10 g. The energy embodied in tungsten carbide could be as high as 576 MJ/kg [14], while the values for HSS are far lower (i.e., about one-sixth, according to Table 1). In addition, the energy necessary to manufacture the cutting insert may be estimated as 1.5 MJ/tool, according to [4]. Therefore, on the basis of these values, and taking into account the high number of processable parts of each tool (Table 2), the contribution of these consumables to the total cradle-to-gate impact can basically be confirmed to be negligible.

Table 2. The cutting tools employed for each OP and the parts processed per tool.

Op.	Tool	Parts per tool
OP 1	Center drill	2500
	Cutting insert for milling	200
	Cutting insert for turning	150
	Parting blade insert	80
OP 3	Grinding wheel (500×125×300 mm)	12000
OP 4	Grinding wheel (250×7×76 mm)	1800
	Grinding wheel (250×8×76 mm)	1800
OP 5	Grinding wheel (400×25×160 mm)	5000

Moreover, other ancillary material inputs that (*i*) are also amortized after the production of multiple parts and/or (*ii*) have a relatively-long functional life, could be excluded from the analysis, such as the glass spheres for sandblasting (OP 6), the

3:100-diluted detergent for cleaning (OP 7), and the target for PVD coating (OP 8). As far as the consumption of oil is concerned, the same kind of lubricating oil is used for all the cutting operations to optimize the logistics, supplier management, and disposal operations. The total mineral oil consumption was quantified as 19 ml/part. Referring to standard values of embodied energy for mineral oil [16], the contribution to CED would be lower than 0.1 MJ/part. As for the gases, during the heat treatment (OP 2), nitrogen was used. For OP 8, apart from nitrogen, hydrogen and argon were also consumed. Despite their impact being modeled with average coefficients [17-19], they can be expected to provide negligible contributions, with respect to the other impacts, on the cradle-to-gate life cycle, given the small percentage of consumables used to produce a single tap. Therefore, the following discussion only focuses on the material production and the electric energy requirements for the manufacturing phase. It is worth noting that the here-reported results are valid for the specific case study and functional unit, as well as for the here-considered metrics (i.e., CED and CO_2 emissions). Should the boundaries and/or the purpose of the study change (e.g., when shifting toward the total environmental impact of the whole company or considering other environmental performance indicators), the here discussed results should be reviewed and revised.

4.3. Process time

Fig. 4 reports a summary of the cycle time measurements per part produced. It highlights that the heat treatment, ultrasonic cleaning and PVD coating are the most time-consuming operations in the plant. These operations are performed in batches; the measured cycle time is defined as the time spent by each part in the system. The charge capacities are detailed in Fig. 1: around 800 parts are simultaneously processed under standard operational conditions. Thus, the related total energy consumption (e.g., 661 kWh for OP 2) has to be divided by the number of parts produced in a single batch. It is worth mentioning that, for practical purposes, the ultrasonic cleaning capacity was kept equal to that of the PVD coating.

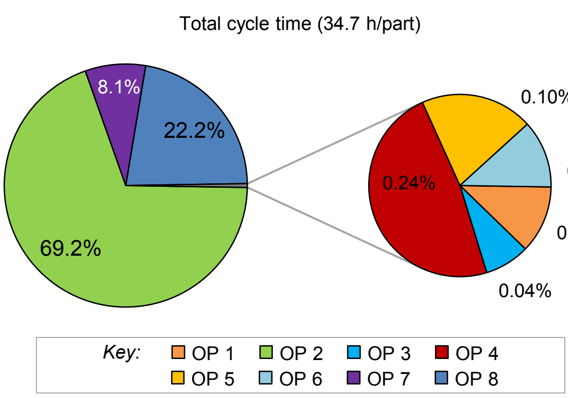

Fig. 4. The total cycle time, with details of each operation.

5. Results and discussion

Fig. 5 reports all the contributions to CED and the total emissions derived from each phase of the assessed life cycle stages. The shares attributable to material production, pre-manufacturing and manufacturing are also detailed. As can be noticed, the electricity consumption affects the Cumulative Energy Demand to a great extent, and it accounts for (at least) half of the CO_2 emissions for the here-considered energy mix. In detail, by grouping the manufacturing operations into macro-groups, 45% of the electric energy demand is devoted to the material removal processes (OPs 1, 3, 4 and 5), 30% to the heat treatment (OP 2), and 25% to the surface treatments (OPs 6, 7 and 8). The heat treatment is the most energy-consuming operation (but also takes up most of the cycle time), although it also processes the highest quantity of parts in a single charge. A total of 67% and of 85% of the electric energy consumption for OP 4 and 5, respectively, is due to the oil filtering through centrifuges. The energy consumption for sandblasting (OP 6) is mostly due to the production of compressed air, which was modeled according to [20].

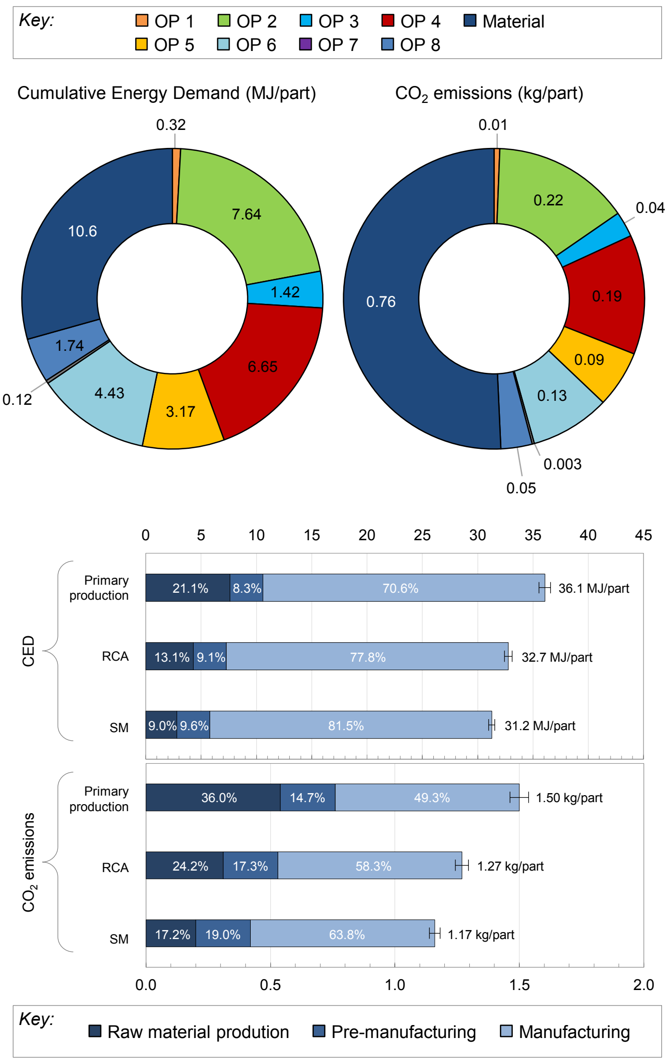

Fig. 5. Summary of the CED (*left*) and CO_2 emissions (*right*), detailing the relative shares of material consumption and electricity.

The assumptions underlying the modeling of the impact of material production have a significant effect on the results. Once the cradle-to-gate burden has been computed, via RCA, the CED and CO_2 emissions lower to 32.7 MJ/part and 1.27 $kgCO_2$/part, respectively, as a result of including a 55%-share of the incoming recycled material. Moreover, the SM (which is a well-established way of measuring future benefits by including the end-of-life within the assessment [13]) allows a further reduction of 1.5 MJ/part and 0.1 $kgCO_2$/part to be achieved, with respect to the RCA. This confirms the importance of using secondary material production routes to minimize the depletion of resources. As far as the CO_2 emissions are concerned, as stated in the EEA, the emission intensity of GHG should decrease by 2030 [12]. This would proportionally affect the here-obtained results.

6. Conclusions and outlooks

The production route of an M10 spiral point tap has been assessed by including the modeling of feedstock material production and manufacturing processes. The Cumulative Energy Demand and CO_2 emissions relative to the material flows, the consumable resources and the energy, were quantified. Unlike the previous study carried out in 2013 on a similar tool [15], the modeling of the material production and pre-manufacturing stages were analyzed, as well as the surface and heat treatments (which previously were considered outsourced operations). The present approach, which monitors all these aspects, is aimed at identifying the weakest points that need to be optimized. According to the obtained results, the electric energy consumption is the most impactful factor, followed by the incoming feedstock material production, whereas the impact of consumables instead was assumed to be negligible. The heat treatment was the most energy- and time-demanding process, followed by the material removal ones. Overall, 36.1 MJ of energy is needed, and 1.5 $kgCO_2$ is emitted to produce an M10 spiral point tap, when primary feedstock material production is considered. An increase in use of material from secondary production (or an increase in end-of-life material recycling) is suggested, as well as the use of greener energy mixes. The forecasted decrease in GHG emission intensity is encouraging, and should lead to lower emissions, regardless of the selection of the parameters for each operation. Notwithstanding these benefits, an optimization of the process parameters could still be important. In such a context, some beneficial effects, due to specifically-developed energy efficiency optimization procedures [21], have been noted. Further technical tests and in-depth studies could support multi-objective optimizations to find the right trade-off between the technical quality requirements and sustainability needs. Moreover, this research could be useful to provide tool data for the life cycle inventory of other studies focused on the environmental impact of thread machining.

CRediT author statement

A.R. Catalano: Methodology, Formal analysis, Writing - Original draft preparation; L. Debernardi: Formal analysis, Data curation; R. Balaso: Investigation, Resources; F. Rubbiani: Investigation, Resources. P.C. Priarone: Conceptualization, Methodology, Supervision; L. Settineri: Supervision, Funding acquisition.

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