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Resource efficiency analysis of lubricating strategies for machining processes using life cycle assessment methodology

Alessio Campitelli*, Jorge Cristóbal, Julia Fischer, Beatrix Becker, Liselotte Schebek

Technical University of Darmstadt, Institute IWAR, Department of Material Flow Management and Resource Economy, Franziska-Braun-Straße 7, 64287, Darmstadt, Germany

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A B S T R A C T

The enhancement of resource efficiency in the manufacturing industry is a major key to achieve sustainable development. The purpose of this paper is to investigate the resource efficiency of metal working processes using different lubrication strategies: flood lubrication (FL) and minimum quantity lubrication (MQL). Life Cycle Assessment (LCA) is a suitable methodology to assess the resource efficiency. In this paper a LCA is carried out for three different materials: aluminium, steel and cast iron. The process related data had been provided by practical measurements on state of the art machines and missing data derived from literature and expert interviews. The used input and output data for the inventory analysis is documented in this paper. In a hotspot analysis using LCA, fourteen impact categories from CML 2001 had been analysed. Finally, parameters with a high influence on the resource efficiency of machining processes were examined.

The results of the LCA show that the significant parameters causing high environmental impacts are electricity, compressed air and FL oil. The comparison of the machining processes using FL and MQL technologies reveals that most of the analysed processes have a higher environmental impact using FL instead of MQL. This is mainly due to the high energy consumption for the lubricating pump and also because of the higher consumption of lubricants compared to MQL. Furthermore, the generation of hazardous waste, in form of used oil and used filter fleece also contributes. The MQL-technology requires less electricity and lubrication oil and avoids hazardous waste. However, the results show that the compressed air consumption of MQL is significantly higher compared to FL-related processes.

Through this study, new and specific LCA datasets for drilling and milling for three working materials including two lubricating strategies (FL and MQL) are generated for further research.

1. Introduction

The industrial sector consumes about 54% of the world's total produced energy (EIA, 2016) and industrial manufacturing for metal-based durables is responsible for around 25% of the primary resource use and more than one third of the global electricity use (UNEP, 2011). The enhancement of resource efficiency in the manufacturing industry is the key to achieve sustainable development.

The European resource policy defines the term “resources” as natural resources including renewable and non-renewable primary raw materials, flow resources (e.g. geothermal, wind, tide and solar energy), environmental media (air, water, soil), spatial resources, biodiversity and other ecosystem resources (European Commission, 2005, 2011). According to the directive VDI-4800–1:2016 of the Association of German Engineers (Verein Deutscher Ingenieure – VDI), the definition for resource efficiency is: “Ratio between a certain benefit or result and the resource use required for it.” (VDI, 2016). Thus, in the context of this paper, an increase in resource efficiency will be accomplished when a certain benefit in goods or services is achieved with a lower use of natural resources or lower environmental burden without affecting the product quality or the process stability.

Life Cycle Assessment (LCA) is a suitable methodology to assess the resource efficiency of products and services within a life cycle approach. LCA offers a holistic approach encompassing all environmental exchanges (i.e. energy, emissions, resources and wastes) occurring during the whole life cycle of a product or a process. The

* Corresponding author.
E-mail address: a.campitelli@iwar.tu-darmstadt.de (A. Campitelli).

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Abbreviations

AP	Acidification potential
CC	Climate change
CNC	Computerized Numerical Control
DAR	Depletion of abiotic resources
EP	Eutrophication potential
FAE	Freshwater aquatic ecotoxicity
FL	Flood Lubrication
FSE	Freshwater sediment ecotoxicity
FU	Functional Unit
HT	Human toxicity
IR	Ionizing radiation
LCA	Life Cycle Assessment
LU	Land use
MAE	Marine aquatic ecotoxicity
MQL	Minimum Quantity Lubrication
MSE	Marine sediment ecotoxicity
PD	Process Drilling
PM	Process Milling
PO	Photochemical oxidation
SME	Small and Medium-Sized Enterprise
SOD	Stratospheric ozone depletion
TE	Terrestrial ecotoxicity
VDI	Verein Deutscher Ingenieure (Association of German Engineers)

use of LCA for process analysis (known as “gate-to-gate”) allows to compare different processes delivering similar functions and to select the most environmental-friendly one, or in this case the most resource efficient. It is also used to identify hotspots in order to prioritize possible improvements in the process’ environmental performance (Jaquemin et al., 2012).

‘Machining’ is the term used to describe the removal of material from a work piece. The main types of machining are drilling, turning, milling and grinding. The effectiveness of machining processes is highly dependent on the presence of cutting fluids that decrease temperatures and cutting forces. Traditionally, flood lubrication (FL) techniques have been used in industry, but they consume high quantities of those fluids resulting in high costs. Besides, those fluids are well known to cause environmental and health issues (Weinert et al., 2004). For that reason, new techniques such as the Minimum Quantity Lubrication (MQL) are under research.

A literature review shows that many studies focused on lubricating techniques from a technical perspective. Sharma et al. (2016) reviewed the effect of MQL in machining processes and its effect on the performance parameters. Boswell et al. (2017) also reviewed more than 600 papers and concluded that MQL has huge potential as a substitute for conventional flood cooling. In the last years, resource efficiency and sustainability of machining processes has gained relevance in literature. Zhou et al. (2016) presented the state of academic insight into the energy consumption model and energy efficiency of machine tools. Ingarao (2017) reviewed the manufacturing strategies of metal shaping processes for efficiency in energy and resources use. Recently, Hegab et al. (2018) presented a general assessment algorithm for sustainable machining processes in which energy consumption is assessed along with other metrics, i.e. machining costs, waste management, personal health and operational safety as well as environmental impact.

Different methodologies and methods, mostly focused on energy, had been used in literature to measure resource efficiency of machining processes such as exergy analysis (Creyts and Carey, 1999; Ghandehariun et al., 2015) or energy models based on the kinematic and dynamic behaviours of selected machine tools (Bi and Wang, 2012). Moreover, Branker and Jeswiet (2012) developed an economic model exemplarily carried out for a milling process to reduce costs, energy consumption as well as carbon dioxide emissions of the process. The use of LCA to assess machining processes is becoming more common in literature, although the combination of environmental impacts considered and the machining processes under assessment changes depending on the study. Several studies narrowed down the number of impact categories analysed within the assessment as in Germani et al. (2016) and Hirohisa et al. (2008), which only considered climate change. Gamage et al. (2016) used the single score of ReCiPe to assess electro discharge machining, even if this single score was calculated including up to seventeen impact categories that were normalized, weighted and summed together. Other studies included more impact categories such as Pusavec et al. (2010) that presented the general issues and methods for achieving production sustainability including a comparative life cycle assessment of alternative machining processes using six different impact categories. Pereira et al. (2016) compared different lubrication strategies for a turning process considering nine impact categories. Fratila (2010) compared the operation of gear milling using near-dry and flood lubrication reporting eleven impact categories. Faludi et al. (2015) compared the environmental impacts of additive manufacturing and traditional machining reporting up to seventeen impact categories.

As shown by the literature review the scope of those papers differ in the machining process, the lubrication techniques under assessment, the cutting material used in the process (e.g. steel, aluminium, titanium) and the impact categories considered. Up to the knowledge of the authors, there is no paper in literature that proposes a resource efficiency assessment of the two main lubrication techniques for the most important machining processes and the most common cutting materials considering a complete set of environmental impact categories. The scope of this paper, and in the end its novelty, is to assess two machining processes (drilling and milling) from gate-to-gate, based on primary data acquisition, for different cutting materials (aluminium, cast iron and steel) and using different lubrication strategies (FL or MQL) in order to conclude which of these lubrication strategies is more resource efficient.

This paper reports the approach as well as the data sets for assessing resource efficiency of lubricating strategies for machining processes using LCA methodology. As a first step, reference processes that represent the state of the art were defined by machining processes, cooling lubrication strategies and cutting materials. As a second step, the life cycle inventory was compiled using foreground data from measurement at state of the art machines, expert interviews and technical documents. For Life Cycle Impact assessment, fourteen different impact categories had been considered. Finally, both a hotspot and a sensitivity analysis had been performed in order to identify the parameters with high influence on resource efficiency and the influence of possible uncertainty in the results, respectively.

The results of this study were the cornerstone for developing a framework for small and medium enterprises (SMEs) to assess resource efficiency of machining processes (Schebek et al., 2016). Within this framework, the reference processes, which represents the state of the art, can be used for benchmarking purposes in

SMEs, i.e. a SME can measure its resource efficiency potential by comparing its own processes to the reference processes presented within this study.

2. Materials and methods

In this chapter, the single steps of the life cycle assessment specified in ISO 14040:2009 (ISO, 2009) and ISO 14044:2006 (ISO, 2006) are described. This section addresses the description of the pilot plant, the goal and scope of the study, the functional unit and reference flows as well as the system boundaries of the product system. Moreover, the life cycle inventory and the impact assessment methods are described and presented.

2.1. Description of the pilot plant

The system under study where all the measurements were taken, is a Computerized Numerical Control (CNC) centre located in the Mechanical Engineering Institute (PTW) within the TU Darmstadt (Germany). The CNC machining centre of type G350 (from the company Grob), shown in Fig. 1, includes a cooling lubricant high-pressure pump that ensures the adequate supply with lubricants during the machining process. The CNC machine does not contain any component that allows the recovery of the lubricant discharged by the chips. Although, this machine permits to connect a mobile device for using MQL.

A FL emulsion for the FL process (Novamet 910; concentration 7%; flow rate 23 l/min) and a bio-based synthetic ester oil (Microtol EC 32; flow rate 6.5 ml/h at a differential pressure of 1.2 bar) for the MQL process, both from the company OEMETA, were used.

As mentioned before, a MQL mobile equipment from Bielomatik was used. It consists of an aerosol system, a pressure reducer and a control, which ensures the supply of the air-oil mixture during the machining process.

Concerning the tools, for drilling a solid-carbide spiral drill was used. For the climb-milling process of aluminium, a milling cutter with turn-over plates coated with polycrystalline diamond was used. For the milling process of steel and cast iron, hard metal milling cutters were used. The tool lives for drilling and milling were considered in the relation to the different processed materials and by assuming a re-sharpening of the tools. The tool lives were determined for each processed material based on the experience of tool manufacturers. According to the tool manufacturers no significant change between the lubrication strategies is noticeable, that is why the tool lives using the MQL or the FL technique were assumed to be the same. The only exception was for the machining of cast iron, here the tool life is usually one third lower for MQL than for FL.

Fig. 1. CNC machining centre of type G350 (Source: PTW/TU Darmstadt).

The resource efficiency analysis of the different lubrication strategies for different machining processes regarding diverse cutting materials was done by means of an LCA following the recommendations of the ISO 14040:2009 (ISO, 2009) and ISO 14044:2006 (ISO, 2006). The software open LCA 1.4.2 (GreenDelta) was used to perform the attributional LCA.

2.2. Goal and scope of the LCA

The scope of the LCA study is to investigate two machining processes (drilling and milling) that cover the most common operations in industrial practice in Germany (VDW, 2014) using two different lubrication strategies (FL and MQL) for different cutting materials (cast iron, aluminium and steel). In this context, the LCA study was carried out to investigate which of these lubrication strategies is more resource efficient considering fourteen different impact categories and to identify the parameters that have a major influence on the resource efficiency of the machining processes.

2.3. Functional unit (FU) and reference flow

For this study, the FU selected was the quantity of drill holes or milled area. Normally, databases such as ecoinvent v3 define the FU for CNC-machining process as the amount of chips produced measured in kilograms. During this study the following CNC machining processes were checked for possible analysis in ecoinvent v3.1 (2014): steel drilling and steel milling, aluminium drilling and aluminium milling, cast iron drilling and cast iron milling. The FUs defined within this study (see Table 1) were considered more comprehensible and more practical for SMEs comparing to the FUs used by ecoinvent, which do not take into account the characteristics of tools (e.g. depth, diameter, tool material, etc.). However, if necessary, there is still the possibility to convert the FU “drill hole” into the FU “amount of chips”.

For milling, two different FUs were defined, due to the different shape of work pieces. The milling of aluminium was done on a cylinder motor block, which contained a lot of holes. On the other hand, the milling of cast iron and steel was done on blocks without holes. For that reason, the milling surface and the milling volume were different. The detailed process parameters are summarized in the Supplementary Material (SM) (see Table SM1).

The reference flows defined in this study for each machining process include the two lubrication strategies (FL and MQL) as shown in Table 1.

2.4. LCA system boundaries

The system boundaries for the investigated machining processes cover the life cycle from gate to gate, only regarding the process itself and not the product (see Fig. 2). Two product systems were defined depending on the lubrication strategy used: FL and MQL. In order to ensure the comparability of the different strategies, the same FUs were used. The geographical scope is Germany.

Within the project LernRess specific datasets for different combinations of machining processes (called hereafter “reference processes”) had been identified. These reference processes are defined by:

1) machining processes (drilling and milling),
2) cooling lubrication strategies (FL and MQL) and
3) cutting materials (aluminium, cast iron and steel).

Table 1
Functional units and reference flows for the defined drilling and milling processes.

	Functional unit (FU)	Reference flows
Drilling process for aluminium, cast iron and steel	3 drill holes with a twist drill (diameter 8.5 mm, drilling depth 5xd) and a produced chip volume of 2.411 mm^3.	• 3 drill holes with FL • 3 drill holes with MQL
Milling process for aluminium	Milling surface of 26.250 mm^2 with a cutting depth of 0.2 mm and produced milling volume of 5.250 mm^3 (= 0.029 kg).	• Milling with FL • Milling with MQL
Milling process for cast iron and steel	Milling surface of 2.345 mm^2 with a cutting depth of 0.2 mm and produced milling volume of 469 mm^3 (= 0.007 kg).	• Milling with FL • Milling with MQL

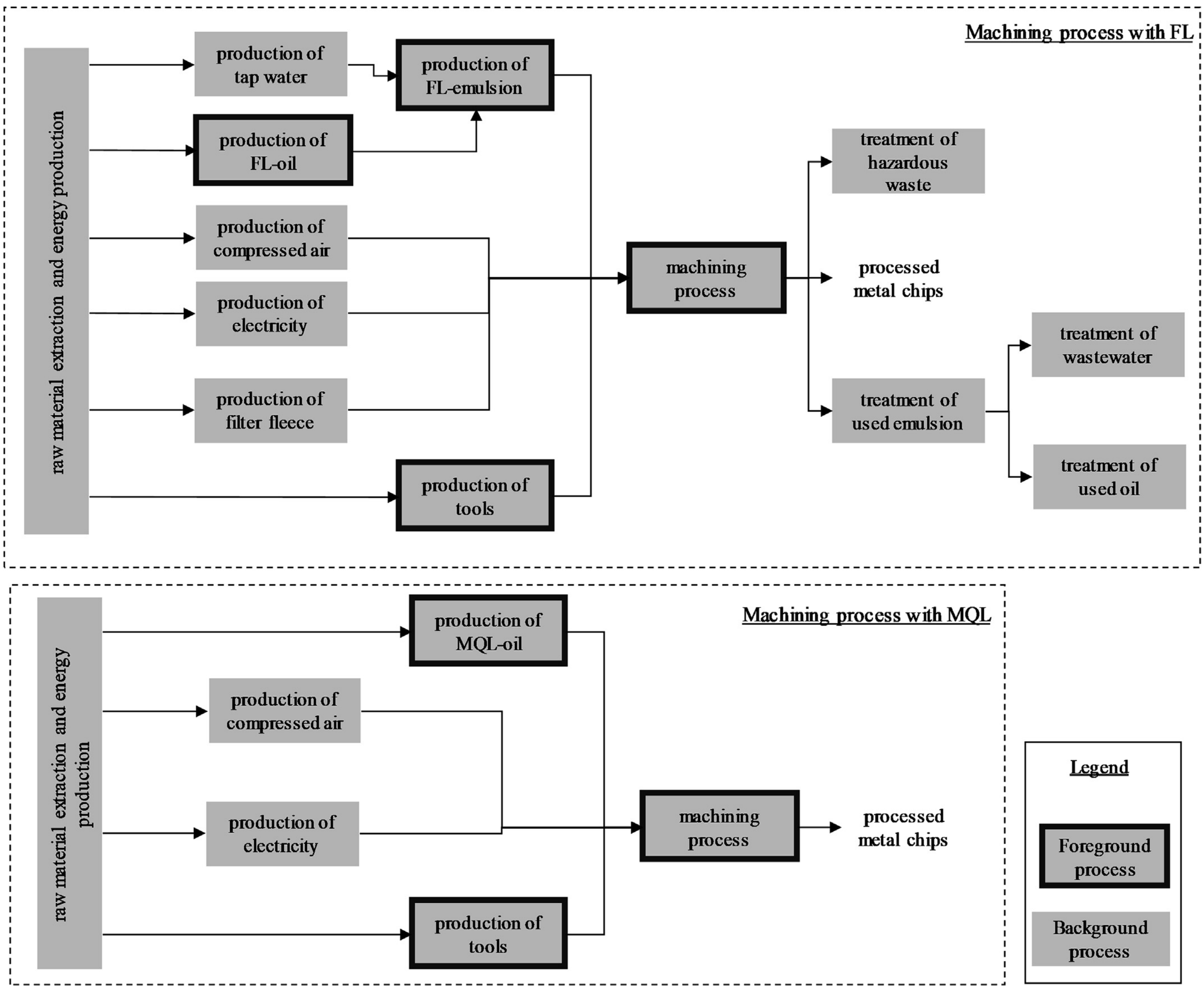

Fig. 2. System boundaries for a machining process using FL and MQL.

The twelve reference processes investigated are shown in Table 2.

The process parameters for each reference process are given in the SM (see Table SM1).

The milling and drilling processes are the main elements of their respective product system (as shown in Fig. 2). The input and output flows of the machining processes (i.e. the upstream (production of input materials) and downstream processes (treatment of waste, waste water and hazardous waste)) were considered. The focus of this study is on the used operating materials (energy, compressed air, lubricants, etc.) and generated waste (hazardous waste and used emulsion) arising during the machining process. Both product systems differ only with respect to the applied lubricants, the filter fleece and the related waste produced.

The flows, which apply to both product systems are not part of the investigation. This means that the production of the used material alloys and the further processing, the use and the End of Life (EoL) phase of the product were excluded. The CNC-machining tool

Table 2
Twelve investigated process (i.e. reference processes) as combination of machining process, working material and lubrication strategy (e.g. PD1-FL, PD1-MQL, PD2-FL, PD2-MQL, etc.).

	Aluminium alloy	Steel alloy	Cast iron	Lubrication strategy
Process drilling (PD)	PD1	PD2	PD3	• Flooding lubrication (FL) • Minimum quantity lubrication (MQL)
Process milling (PM)	PM1	PM2	PM3	• Flooding lubrication (FL) • Minimum quantity lubrication (MQL)

and the air compressor, which are required for both processes, are not part of the assessment, because we assumed that the machine consumption by using FL or MQL are marginally small regarding to the FU. Downstream cleaning processes were not included in the system boundary since the investigation refers exclusively to the machining process. The inclusion of cleaning processes is only considered useful, if a complete product is manufactured and the whole production chain of the product is defined.

2.5. Life cycle inventory

The collaboration with the PTW Institute of TU Darmstadt permitted to collect the needed primary data for the foreground processes on their own CNC centre in 2015. Data gaps in foreground data had been complemented from technical literature and by expert interviews. Background data and processes were taken from the ecoinvent database v3.1. In the SM more information about how data was generated for the relevant parameters is given (see Table SM2).

Table 3 and Table 4 contain an overview of the used data for the foreground and background processes. The modelled product systems in this study are specific and are not directly comparable with the machining processes from the ecoinvent databases, because the ecoinvent datasets for the machining processes drilling and milling with CNC are very general and its validity is no longer guaranteed for ecoinvent v3.4. The datasets for the machining processes (i.e. steel drilling - CNC, steel milling - CNC, aluminium drilling - CNC, aluminium milling - CNC, cast iron drilling - CNC and cast iron milling - CNC) from the ecoinvent v3.4 were already contained in ecoinvent v2.2 from 2010 and no update was done since the transfer in ecoinvent v3. So, the data refers to the publication of Steiner et al. (2007) and also some data is based on publications of Barnes (1976) and Degner and Wolfram (1990) as well as of companies from the years 2003–2006 (Steiner et al., 2007).

Additionally, ecoinvent does not specify the different kind of lubrication strategies and the process itself does not contain the drilling or milling tools, only the “metal working machine-unspecified”, which contains the material composition of machines from European producers, but without naming a specific technology. The process “lubricating oil” was updated in ecoinvent v3.4 and additives were included with regard to the publication of Raimondi et al. (2012) in comparison to ecoinvent v3.1. The modelled “lubricating oil” in ecoinvent v3.4 is based on 80% mineral oil, whereas the modelled FL oil in this study contains only 30% mineral oil and 30% fatty acids. For the modelling of the FL oil in this study also additives (e.g. emulsifier and polycarboxylates) were included.

The inventory data of the twelve reference processes are part of the SM, wherein the input and output data for the investigated processes for drilling are listed in Table SM3 (drilling processes PD1 – PD3) and in Table SM4 for milling (milling processes PM1 – PM3).

2.6. Life cycle impact assessment

The CML 2001 method (Althaus et al., 2010) from ecoinvent v3.1 was used for the impact assessment. In order to ensure a comprehensive analysis, the fourteen impact categories from CML 2001 were reported and analysed. For the normalization of the results, normalization factors from CML 2001 (non baseline) EU25 + 3, year 2000 obtained from open LCA LCIA methods v1.7 were used. This allows a consistent estimation of the relevance of each impact category regarding the investigated processes. Table 5 shows the impact categories selected and the normalization factors.

No allocation method had been applied, since the environmental impacts are only accounted for the process, which is represented by the FU.

3. Results and discussion

The characterized results of the impact assessment as well as the normalized values are reported individually for drilling (see 3.1.1) and milling (see 3.1.2). Section 3.1.3 focuses on the detailed results for the impact categories that presented more relative importance after normalization (i.e. DAR) and two other impact categories considered as strategic (i.e. CC and LU).

3.1. Drilling

The impact assessment results for all the impact categories (CML, 2001) of the drilling processes (PD1 to PD3) are shown in Table 6.

Results for drilling aluminium (PD1) show that PD1-FL performs better than PD1-MQL in almost all impact categories, except for LU and TE, mainly due to the FL oil. For all other impact categories PD1-MQL has a greater impact due to the higher consumption of electricity for the machining process and compressed air.

For steel (PD2), impacts of PD2-FL are higher than PD2-MQL in all categories, being for CC, LU, PO and TE even double higher, mainly because of high consumption of FL oil (e.g. the consumption of FL oil in PD2-FL is 65 g per drill hole in comparison to 4.83 g per drill hole in PD1-FL and 3.86 g per drill hole in PD3-FL).

Finally, for cast iron (PD3) the results for both processes are very close being the most contributing flows for almost all categories electricity and compressed air, except for TE in which the main contributors within PD3-MQL are the process of electricity used (58%) and the MQL oil (25%) and in the case of PD3-FL the contribution for this category is mainly depending on electricity (54%) and FL oil (37%).

Normalized values show the relative importance of impact categories and in this case DAR is by far the most important impact category (more than 90%), followed by FSE (around 4%) and the FAE, MSE and MAE (around 1.5% each). The rest of impact categories present a contribution of less than 1%.

3.2. Milling

The impact assessment results for the fourteen impact categories (CML, 2001) of the milling processes (PM1 to PM3) are shown in Table 7.

The results for milling aluminium (PM1) show that PM1-FL

Table 3
Overview of the used input- and output-flows for the foreground processes. *Note: the product of each process is underlined.

Foreground processes with primary data from measurements and interviews			
Process	FU	Description	Flow-data
Machining processes	See Table 1	See Table 2	**Input-flow:** electricity compressed air FL-oil MQL-oil filter fleece drilling tool **Output-flow:** 3 drill holes / milling surface used filter fleece used emulsion
FL-oil	[1 kg]	This process describes the formulation of a water-miscible FL-concentrate. The FL-oil consists of: 30% of mineral oil 15% of fatty acids 20% polycarboxylates 20% emulsifier 15% other additives and water. The processes packaging (incl. packing materials), filling and any transports to the customer are not part of this process. **Technical flows:** Viscosity 43 mm^2/s Relative density 973 g/ml	**Input-flow:** electricity heat in chemical industry glycol (ethylene glycol) diesel emulsifier (dimethylamine) polycarboxylates water compressed air fatty acid **Output-flow:** FL-oil used oil wastewater municipal solid waste
FL-emulsion	[1 kg]	This process consists of 7% FL-oil and 93% of water to form FL-emulsion.	**Input-flow:** FL-oil water **Output-flow:** FL-emulsion
MQL-oil	[1 l]	This process describes the formulation of an MQL-oil. The oil consists of 75% of a synthetic ester oil. The processes packaging (incl. packing materials), filling and any transports to the customer are not part of this process. **Technical flows:** Viscosity 32 mm^2/s Relative density 914 g/ml	**Input-flow:** electricity glycol (ethylene glycol) water compressed air fatty acid additive (toluene, liquid) **Output-flow:** MQL-oil used oil wastewater municipal solid waste
Solid carbide drill	[item]	The manufacturing of a solid carbide drill is considered. The process includes the separation of the raw rod, the grinding work on the CNC machine and the grinding of the grooves as well as the cleaning process. **Technical Flows:** Diameter: 8,5mm No. of cutting edges: 2 2 cooling channels Cutting depth: 5xD	**Input-flow:** electricity lubricating oil steel water compressed air foam cleaner (fatty alcohol sulphate) **Output-flow:** Solid carbide drill used oil wastewater hazardous waste
Polycrystalline diamond milling cutter	[item]	The manufacturing of a polycrystalline diamond milling cutter is considered. The complete processing of the milling cuter, without the cleaning process, is modelled. **Technical Flows:** Diameter: 80 mm No. of cutting edges: 10 4 cooling channels Tool life: 6000 m	**Input-flow:** electricity lubricating oil steel water compressed air **Output-flow:** Polycrystalline diamond milling cutter used oil wastewater hazardous waste

performs worse than PM1-MQL in all impact categories mainly because of the use of electricity. The flow FL oil has also a great contribution on the following impact categories: LU (53%), PO (32%) and TE (89%).

For the case of steel (PM2), the FL-related process (PM2-FL) has a greater impact in each impact category comparing to PM2-MQL, in which the main contributor is the used electricity. But, as for PM1, FL oil influences considerable on LU (44%), PO (25%) and TE (84%).

Finally, for cast iron (PM3) the impact of PM3-MQL is higher in most of the categories comparing to the performance of PM3-FL

Table 4
Overview of the used input- and output-flows and their background processes.

Used input- and output-flows and their background processes taken from ecoinvent v.3.1		
Flows	**Process in ecoinvent**	**Note**
Hazardous waste	treatment of hazardous waste, hazardous waste incineration – CH	–
Filter fleece	market for fleece, polyethylene – GLO	There is no significant weight change for "new" filter fleece compared with used filter fleece. Due to this, the quantities of the in- and output can be assumed to be the same.
Used oil	treatment of waste mineral oil, hazardous waste incineration, alloc. default, U – CH	FL discharge is assumed to be waste oil (without wastewater), which gets recycled. The chips with attached FL are recycled by melting. The mass of the discharged emulsion over chips is included in this process.
Wastewater	treatment of wastewater from lorry production, capacity 4.7E10 l/year – CH	We assume that the composition of the wastewater is comparable to wastewater of other machining processes.
Compressed air	market for compressed air, 600 kPa gauge – GLO	–
Electricity	market for electricity, low voltage – DE	–
Tap water	market for tap water - Europe without Switzerland	–

Table 5
Normalization Factors CML 2001 (non baseline) EU25 + 3 (open LCA LCIA methods v1.7.).

Impact category	*Acronym*	*Units*	*Normalization Factors*
Acidification potential	AP	kg SO2-Eq	1.75E+10
Climate change	CC	kg CO2-Eq	5.21E+12
Depletion of abiotic resources	DAR	kg antimony-Eq	3.16E+07
Eutrophication potential	EP	kg NOx-Eq	1.53E+10
Freshwater aquatic ecotoxicity	FAE	kg 1,4-DCB-Eq	1.89E+11
Freshwater sediment ecotoxicity	FSE	kg 1,4-DCB-Eq	1.77E+11
Marine aquatic ecotoxicity	MAE	kg 1,4-DCB-Eq	6.55E+11
Marine sediment ecotoxicity	MSE	kg 1,4-DCB-Eq	8.83E+11
Human toxicity	HT	kg 1,4-DCB-Eq	3.68E+11
Ionizing radiation	IR	DALYs	6.10E+4
Land use	LU	m^2*a	3.27E+12
Photochemical oxidation	PO	kg ethylene-Eq	3.57E+09
Stratospheric ozone depletion	SOD	kg CFC-11-Eq	1.05E+07
Terrestrial ecotoxicity	TE	kg 1,4-DCB-Eq	1.60E+10

Table 6
Characterized results of the investigated drilling processes (PD1 – PD3). *Note: the units of the single impact categories are listed in Table 5.

Drilling process	PD1 (Aluminium)		PD2 (Steel)		PD3 (Cast iron)	
Impact category	PD1-FL	PD1-MQL	PD2-FL	PD2-MQL	PD3-FL	PD3-MQL
AP	1.30E-04	1.70E-04	2.70E-04	2.00E-04	2.70E-04	2.80E-04
CC	5.51E-02	5.58E-02	1.21E-01	6.75E-02	1.22E-01	1.10E-01
DAR	4.00E-04	4.20E-04	7.30E-04	5.00E-04	9.10E-04	8.20E-04
EP	7.51E-05	8.64E-05	1.60E-04	1.00E-04	1.60E-04	1.50E-04
FAE	4.67E-02	4.91E-02	7.07E-02	5.97E-02	1.08E-01	9.81E-02
FSE	1.02E-01	1.08E-01	1.50E-01	1.31E-01	2.37E-01	2.16E-01
MAE	1.58E-01	1.67E-01	2.35E-01	2.03E-01	3.67E-01	3.32E-01
MSE	1.75E-01	1.86E-01	2.52E-01	2.26E-01	4.06E-01	3.70E-01
HT	1.29E-02	1.51E-02	2.74E-02	1.88E-02	2.72E-02	2.67E-02
IR	4.65E-10	5.54E-10	6.61E-10	6.55E-10	1.04E-09	9.99E-10
LU	4.89E-03	4.53E-03	1.85E-02	5.49E-03	9.86E-03	8.72E-03
PO	6.69E-06	7.87E-06	1.71E-05	9.34E-06	1.36E-05	1.33E-05
SOD	5.02E-09	5.51E-09	1.05E-08	6.56E-09	1.09E-08	1.02E-08
TE	1.20E-04	6.65E-05	1.08E-03	8.40E-05	1.70E-04	1.20E-04

mainly due to the flows of electricity and compressed air. Only for LU and TE the impact is higher in PM3-FL being, as in the other milling processes, the contribution of FL oil process of 45% for LU and 84% for TE.

The normalized values show, as in the case of PD, that DAR is by far the most important impact category (more than 90%), followed by FSE (around 4%) and the FAE, MSE and MAE (around 1.5% each). The rest of impact categories present a contribution of less than 1%. For that reason, in the next section, results for DAR are analysed more in detail. Besides, results for the category of CC are also analysed due to their political relevance and for the category of LU due to the discussions on the use of vegetable oils that require more land.

3.3. Detailed results for DAR, CC and LU

As expected, Fig. 3 shows that the highest contribution to DAR is from energy provision which is reflected in the electricity and compressed air consumption that together account for between 70 and 100% for all processes. The elementary flows that contribute most are the lignite and hard coal used for electricity production within the electricity mix. Depending on the process under assessment, the machining tool production can have certain relevance in the DAR, being up to 15% for some milling processes (PM1 or PM3) but being almost negligible for all drilling processes (PD). In the cases in which the tool production presents a higher

Table 7
Characterized results of the investigated milling processes (PM1 – PM3). *Note: the units of the single impact categories are listed in Table 5.

Milling process	PM1 (Aluminium)		PM2 (Steel)		PM3 (Cast iron)	
Impact category	PM1-FL	PM1-MQL	PM2-FL	PM2-MQL	PM3-FL	PM3-MQL
AP	3.20E-04	2.60E-04	1.90E-04	1.60E-04	2.10E-04	2.40E-04
CC	1.43E-01	9.94E-02	8.32E-02	6.60E-02	8.34E-02	8.42E-02
DAR	9.50E-04	7.40E-04	5.80E-04	4.90E-04	5.90E-04	6.30E-04
EP	1.90E-04	1.40E-04	1.10E-04	9.21E-05	1.20E-04	1.30E-04
FAE	1.04E-01	8.89E-02	6.51E-02	5.91E-02	6.46E-02	7.49E-02
FSE	2.24E-01	1.96E-01	1.41E-01	1.30E-01	1.40E-01	1.65E-01
MAE	3.48E-01	3.02E-01	2.19E-01	2.00E-01	2.18E-01	2.54E-01
MSE	3.80E-01	3.36E-01	2.41E-01	2.22E-01	2.40E-01	2.83E-01
HT	3.34E-02	2.67E-02	1.94E-02	1.65E-02	2.07E-02	2.39E-02
IR	9.68E-10	9.19E-10	6.16E-10	5.94E-10	6.55E-10	8.03E-10
LU	1.71E-02	8.03E-03	9.34E-03	5.58E-03	9.36E-03	6.85E-03
PO	1.83E-05	1.27E-05	1.05E-05	8.03E-06	1.14E-05	1.15E-05
SOD	1.25E-08	9.31E-09	7.48E-09	6.06E-09	7.78E-09	8.07E-09
TE	7.80E-04	1.20E-04	3.70E-04	1.00E-04	3.70E-04	1.10E-04

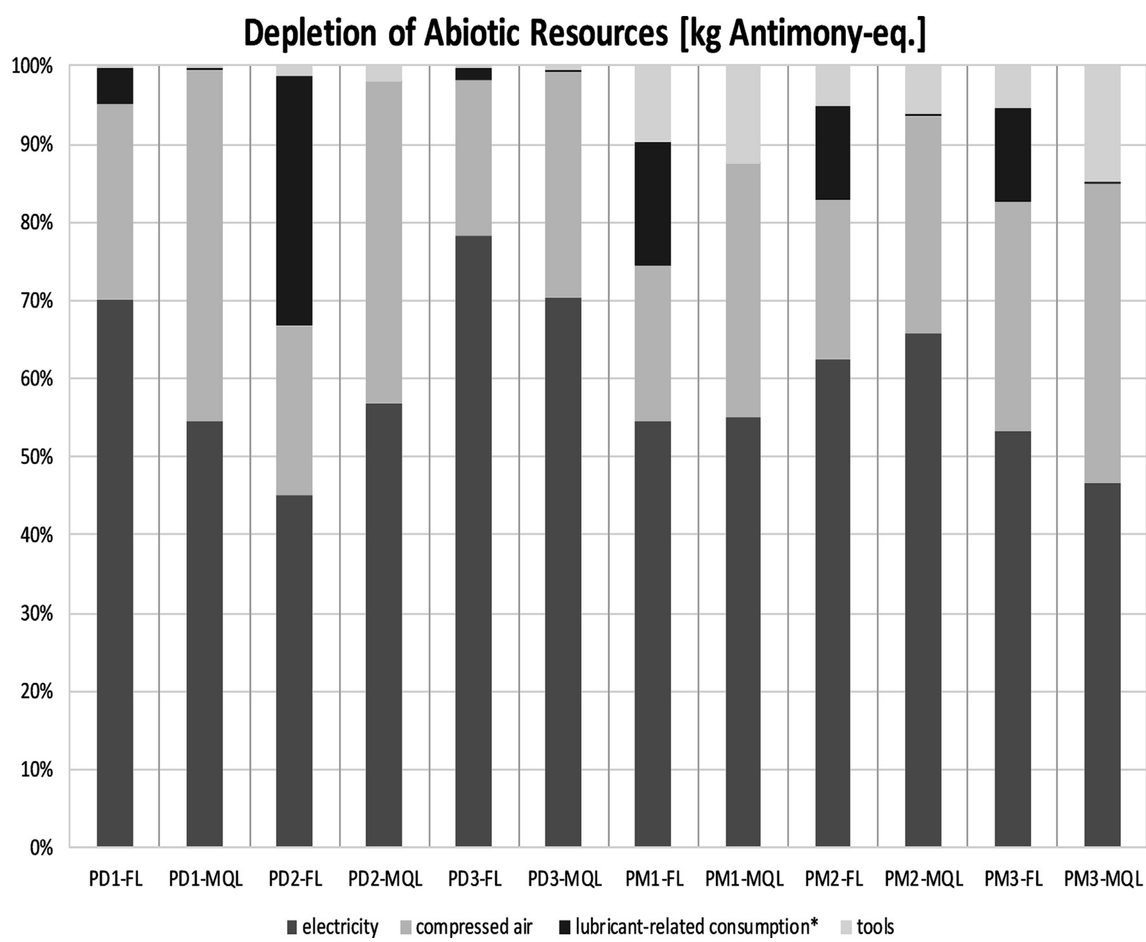

Fig. 3. Detailed results for the impact category Depletion of Abiotic Resources (DAR). *Note that for processes with FL: FL oil, used oil, filter fleece, used filter fleece; for processes with MQL: MQL oil.

contribution, the main elementary flow are lignite and hard coal used for electricity production. Finally, the contribution of lubricant-related processes to DAR is only significant in certain machining process using FL being even up to 33% as in PD2-FL (for the MQL processes it is always negligible). In this cases, the elementary flow that contributes the most is the diesel contained in the FL oil.

Fig. 4 shows the contribution of the reference processes to the impact category CC. Similarly, to DAR, the most important contributions for both technologies (FL and MQL) are the flows of electricity and compressed air (and thus energy provision) with a joint contribution of at least 55% up to 99%. Carbon dioxide (fossil origin) is the elementary flow that contributes the most, coming from the supply of energy by hard coal and lignite.

The contribution of lubricant-related consumption processes to CC is also high being for some of the FL processes up to 47% (being negligible for all MQL processes). These values are mainly due to the waste treatment process of the used oil (combustion is the end of

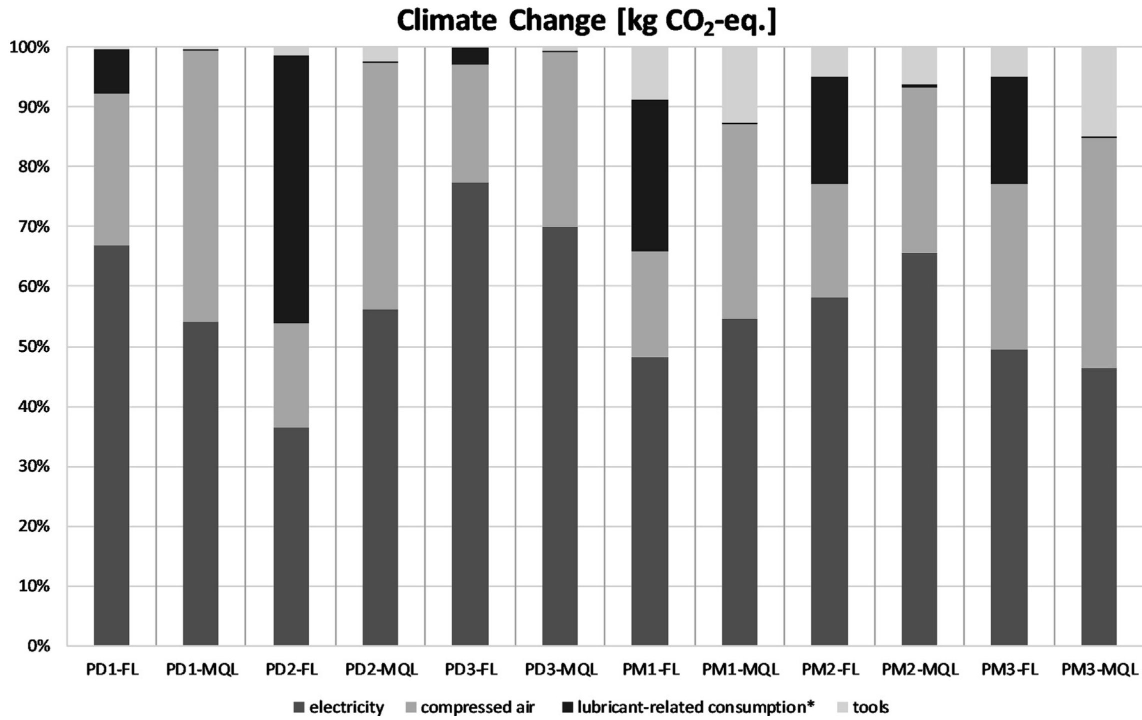

Fig. 4. Detailed results for the impact category Climate Change (CC). *Note that for processes with FL: FL oil, used oil, filter fleece, used filter fleece; for processes with MQL: MQL oil.

life treatment selected). The FL oil production can also have a high contribution to CC due to the containing fatty acids and the emulsifiers, whose production can contribute between 2 and 20% depending on the consumed FL-emulsion during the machining process. Furthermore, the output-flow hazardous waste is relatively high in PD2-FL, because the chip structure leads to more oil remaining on the chips, which ultimately can no longer be recirculated and has to be disposed.

Fig. 5 shows that the most contributing processes to LU impact category are lubricant-related consumption and electricity. On the one hand, lubricant-related consumption contributes up to 70% for some FL processes. On the other hand, electricity has a contribution up to 70% in MQL processes. The high impact of lubricants in LU is due to the fact that the modelled cooling lubricant consists of 30% of mineral oil and 15% vegetal fatty acids. These fatty acids, which can consist of palm oil or soy oil have a large use of land associated. The ester oil for the MQL consists to 100% of fatty acids from vegetable origin. However, the MQL oil does not have such a large LU impact since the quantity needed for the process is very small (i.e. only few millilitres).

The contribution of electricity production to LU is mainly due to the use of wood pellets for the German electricity production. Thus, the LU is strongly influenced by the type of energy which is used for the electricity mix.

The input-flow filter fleece has always an impact less than 1%, and the drilling tool less than 3%. The contribution of the milling tool for the FL-related processes is between 2 and 10% for all impact categories and for the MQL-related processes it is in a range of 4–15%.

3.4. Sensitivity analysis

In order to analyse the uncertainties of the results, a sensitivity analysis was carried out. For the sensitivity analysis, only one parameter per process, which is contained in both FL- and MQL-related processes, was changed. Three scenarios (see Table 8) had been developed to check the sensitivity of the identified relevant flows:

A) 25% reduction of lubricant consumption (FL and MQL),
B) 25% reduction of energy consumption and
C) 100% mineral oil based lubricants.

Changes in MQL-consumption, which in reality can correlate with a change in compressed air consumption, were not considered in the analysis.

Table 9 contains the ranges of the changes for all investigated processes divided in FL- and MQL-based processes for the different processes of drilling and milling by scenario. Only a selection of the most relevant impact categories is shown in the analysis.

As shown in Table 9, a reduction of the lubricant consumption (Scenario A) affects mostly the impact categories LU and TE reducing those impacts up to −18% and −24%, respectively. FL processes present a higher environmental benefit when reducing the quantity of lubricant compared to the MQL processes since the former presents larger quantities of FL-consumption. It could be noted that the MQL processes are generally not very sensitive to the reduction of lubricant consumption.

In contrast to scenario A, the reduction of energy consumption (Scenario B) has a high impact on all impact categories for both FL and MQL processes reducing always the environmental impact. This analysis shows that the parameter “electricity” has an important role in the results.

Finally, the substitution of the biotic parts of the FL emulsion has a great influence on the results (Scenario C). For the fatty acid-dependent impact categories such as LU and TE, the impact is reduced up to −53% and −89% for FL processes and up to −11% and −43% for MQL processes, respectively. This clearly proves a correlation between the lubricant use and those impact categories mainly because of the containing vegetal fatty acids in the FL emulsion and the MQL oil. It is clear that the effect on FL is more important than on MQL processes due to the high quantity of FL

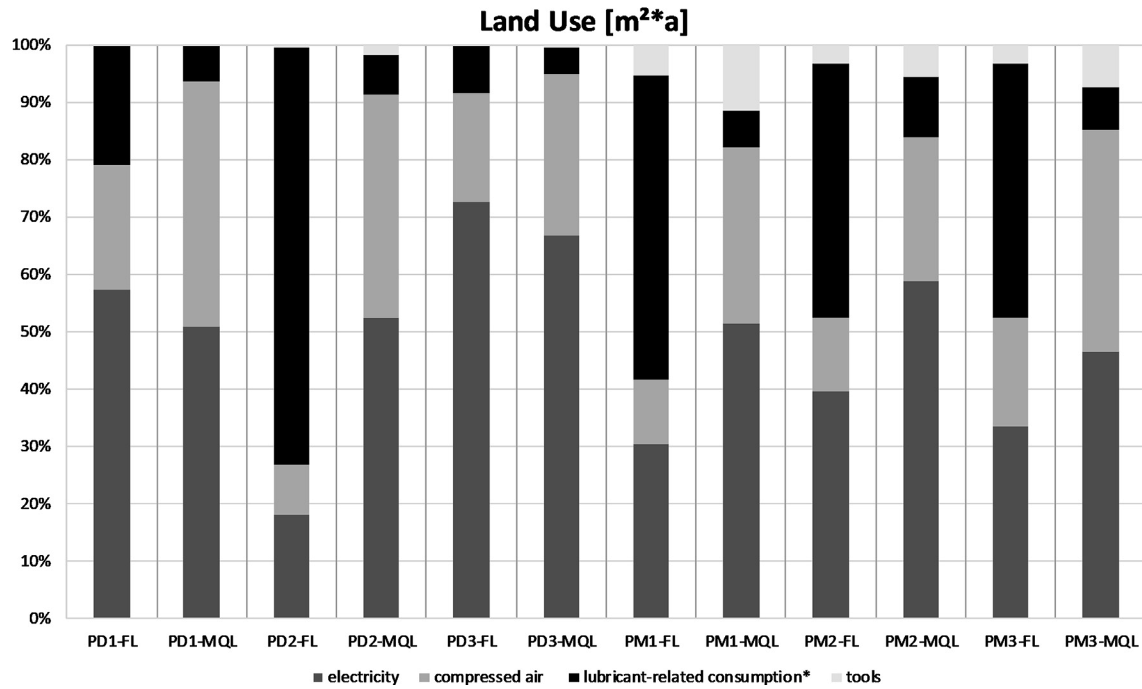

Fig. 5. Detailed results for the impact category Land Use (LU). *Note that for processes with FL: FL oil, used oil, filter fleece, used filter fleece; for processes with MQL: MQL oil.

Table 8
Scenario description for the sensitivity analysis.

Scenario	Description	Comment
A	Reduce lubricant consumption by 25% - for FL-related processes by reduction of the FL-discharge - for MQL-related processes by optimizing the MQL-oil	• These 25% describes the technically feasible savings that can be achieved for MQL. • Normally, for FL-related processes higher savings are possible. But in order to compare the effect of the lubricants, we selected a similar value to the technically feasible savings that can be achieved for MQL.
B	Reduce energy consumption by 25% - for FL-related processes by optimizing the setting of the FL high-pressure pump - for MQL-related processes by using a different MQL-system (2-channel system)	–
C	Use 100% mineral-oil based lubrication	• The biotic substances in the lubricants are totally replaced by mineral oil. This scenario is being investigated to check the effect of mineral oil on the results.

emulsion used. Due to the small MQL oil consumption, the impact reduction is very small (~1%) for almost all impact categories except for LU and TE as mentioned before. As shown in Table 9, FL processes present a large increase in environmental impacts such as CC, DAR and SOD up to +105%, +541% and +909%, respectively, mainly due to the use of diesel to substitute the fatty acids from vegetal origin.

4. Conclusion

This paper presents new primary life cycle inventory data for the machining processes drilling and milling on CNC machines in combination with two lubrication strategies (FL and MQL) as well as three working materials (aluminium, steel and cast iron).

The assessment of machining processes based on the compiled life cycle inventory revealed that most of the analysed processes have a greater environmental impact using FL instead of MQL. This is mainly due to the high energy consumption for the lubricating pump and also because of the higher consumption of lubricants compared to MQL. Furthermore, the generation of hazardous waste, in form of used oil and used filter fleece also contributes. The MQL technology requires less electricity and lubricating oil and it avoids hazardous waste. However, we found out that the compressed air consumption of MQL is significantly higher compared to FL.

The sensitivity analysis proves an existing correlation between the lubricants and the impact categories TE and LU, mainly because of the containing vegetal fatty acids in the FL emulsion and the MQL oil. Moreover, the sensitivity analysis verified the great importance of the parameters energy consumption and lubricant use.

The results of the hotspot analysis based on LCA show that the relevant parameters on the process level causing high environmental impacts are electricity, compressed air and FL oil. Hence, these three parameters are crucial for determining the overall resource efficiency of such machining processes. This finding enables practitioners to perform a robust assessment of the resource efficiency of real production processes by an easy and time-efficient measurement of only their consumption of electricity, compressed air and FL oil. This is a substantial advantage in particular for SMEs, which usually neither have the necessary expertise nor the time to perform a comprehensive evaluation and life cycle assessment of their processes.

Concerning future research, the following directions of work can

Table 9
Results of the sensitivity analysis for all scenarios. Results are expressed as change in % of the scenario regarding the base case (i.e. positive values represent an increase of the environmental impact and negative values a decrease of the environmental impact).

Scenario	Scenario A				Scenario B				Scenario C			
	25% lubricant reduction				25% energy reduction				use of 100% mineral-oil based lubricants			
	PD FL	MQL	PM FL	MQL	PD FL	MQL	PM FL	MQL	PD FL	MQL	PM FL	MQL
Impact category	Change (%)				Change (%)				Change (%)			
CC	−0.3 to −4	−0.05 to −0.1	−1.8 to −2.3	−0.1	−9 to −19	−14 to −18	−12 to −15	−12 to −16	+105 to +6	−0.2 to −0.3	+60 to +47	−0.3 to 0.5
DAR	−0.5 to −8	−0.02	−3 to −4	−0.02 to −0.04	−11 to −20	−14 to −18	−13 to −16	−12 to −16	+541 to +27	−0.2 to −0.7	+279 to +204	+1 to −2
EP	−0.2 to −9	−0.10 to −0.15	0 to −5.2	−0.15 to −0.28	−8 to −17	−10 to −14	−10 to −12.3	−9 to −13	+294 to +16	−0.44 to −2.7	+163 to +120	+2.8 to −2.4
FAE	−0.2 to −4	−0.05	−0.01 to −1.7	−0.05 to −0.09	−14 to −20	−14 to −18	−15 to −17	−12 to −17	+111 to +4	−0.1	+51 to +37	−0.1 to −0.2
LU	−2 to −18	−1 to −2	−11 to −13	−1.6 to −2.6	−5 to −18	−13 to −17	−8 to −10	−11 to −15	−6 to −53	−5 to −7	−32 to −39	−6 to −11
PO	−1 to −13	−0.25	0 to −8	−0.3 to −0.5	−5 to −15	−8 to −12	−8 to −10	−7 to −11	+419 to +32	−0.7 to −0.9	+265 to +193	−1 to −2
SOD	−1 to −10	−0.02	0 to −5.6	−0.02 to −0.04	−9 to −18	−11 to −15	−11 to −13	−10 to −15	+909 to +52	−0.3 to −0.5	+513 to +376	+0.9 to +0.5
TE	−11 to −24	−3 to −9	−0.6 to −22	−5 to −11	−1 to −15	−11	−2 to −3	−8 to −12	−35 to −89	−22 to −34	−79 to −83	−30 to −43

be envisaged from this paper: first, the approach to assess resource efficiency of drilling and milling processes can be transferred to investigate other production processes, provided that suitable equipment for measuring process parameters is accessible. From such hot spot analysis, further values for benchmarking resource efficiency of SMEs can be derived based on a comprehensive methodology and on transparently documented and high-quality inventory data. Second, data sets provided here can be used for compiling life cycle inventories for full production process chains in metal working industry. Here, the research interest may be either the assessment of the contribution of the production phase to the full life cycle of a product or the optimization of a production line on its own. As to the latter, currently novel topics for research arise from the introduction of innovative technological processes as additive manufacturing or the digital transformation of process chains or enterprises along with the concept of Industry 4.0. The investigation of resource efficiency of these novel concepts is currently in its infancy but could be based on the same methodological approach presented here, using the inventory data for the conventional processes of milling and drilling as reference processes.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.jclepro.2019.03.073.

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