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Assessing carbon dioxide emission reduction potentials of improved manufacturing processes using multiregional input output frameworks

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Abstract

Evaluating innovative process technologies has become highly important within the last decades. As standard tools different Life Cycle Assessment methods have been established, which are continuously improved. While those are designed for evaluating single processes they run into difficulties when it comes to assessing environmental impacts of process innovations at macroeconomic level. In this paper we develop a multi-step evaluation framework building on multi regional input-output data that allows estimating macroeconomic impacts of new process technologies, considering the network characteristics of the global economy.

Our procedure is as follows: i) we measure differences in material usage of process alternatives, ii) we identify where the standard processes are located within economic networks and virtually replace those by innovative process technologies, iii) we account for changes within economic systems and evaluate impacts on emissions.

Within this paper we exemplarily apply the methodology to two recently developed innovative technologies: longitudinal large diameter steel pipe welding and turning of high-temperature resistant materials. While we find the macroeconomic impacts of very specific process innovations to be small, its conclusions can significantly differ from traditional process based approaches. Furthermore, information gained from the methodology provides relevant additional insights for decision makers extending the picture gained from traditional process life cycle assessment.

Keywords
Sustainability assessment, multi-regional input-output data, life-cycle assessment, greenhouse gas mitigation, process innovations, economic wide technology replacement

1. Introduction

The recent 5th Assessment Report by the Intergovernmental Panel on Climate Change (IPCC, 2014a) highlights the urgency to act on climate change mitigation if agreed global warming stabilization targets were to be met. Assessing historical developments as well as model based scenarios of possible transition pathways, the IPCC underlines the importance of technological progress in order to achieve ambitious goals.

Even though industrial sectors currently emit more than 30% of global GHG emissions (IPCC, 2014b), their cumulated impacts are estimated to be by far larger due to their influence on emissions caused by related pre- and post-processes such as infrastructure, transportation, material usage or electricity generation (IPCC, 2014b). A relevant share of technological innovations, is located and implemented in industrial sectors (Saygin et al., 2011). In practice those innovations take place at the micro level, where single processes are improved.

Assessing potential macro-economic impacts of technological innovations at process level occurs to be highly non-trivial due to complex interactions within production chains and markets forces. In practice, conclusions are drawn at the micro level by applying Life Cycle Assessment (LCA) methodologies that have become standard for assessing single processes (innovations). Most prominently Process LCA (PLCA), Input-Output LCA (IOLCA) and combinations of both, Hybrid LCA (HLCA) are applied (Guinée, 2011; Suh and Huppes, 2005). While using LCA approaches allow to assess single processes an overall macroeconomic estimation of possible impacts is hardly possible, a research need commonly identified in the literature (Egilmez et al., 2013).

Frequently used PLCA represents a standardized bottom-up approach, where starting with the investigated process, upstream and downstream stages are traced until a predefined system boundary is reached (ISO 14044, 2006; Suh and Huppes, 2005). Considered flows are used to quantify impacts on various indicators including environmental impacts, human health or global warming (Finkbeiner, 2012; Finkbeiner et al., 2006; Klöpffer and Grahl, 2014). PLCA modelling shows to have a high level of detail and many available impact indicators as detailed process databases are available (Finnveden et al., 2009), which enables the calculation of Use- and End-of-Life phase, but suffers from system incompleteness (Suh et al., 2004). The resulting underestimation of impacts related to the production of goods results in so called truncation errors. Estimates on truncation errors vary (Junnila, 2006; Lenzen, 2000; Norris, 2002; Rowley et al., 2009), but suggest significant influence. Furthermore, specific sectors are not (sufficiently) considered (Junnila, 2006; Majeau-Bettez, 2011). It has been further highlighted that PLCA has specific shortcomings when decomposing supply chains at the macroeconomic level distinguishing contributions of drivers, providing relevant information for politicians (Feng et al., 2011; Kucukvar and Samadi, 2015; Kucukvar et al., 2015; Wiedmann et al., 2010).

IOLCA utilizing input output data has been developed as an alternative. Even though IOLCA is “system complete”, as an infinite number of upstream production stages can be traced via a power series, it has been criticized for aggregating economic sectors and assuming homogeneity therein (Finnveden et al., 2009; Majeau-Bettez, 2011; Suh et al., 2004), which can cause under- or overestimates of consumption based impacts associated to production (Rowley et al., 2009). Furthermore, when using IOLCA it is hardly possible to account adequately for the End-of-Life- and Use phase (Suh and Huppes, 2005). However, IO databases consider sectors that are neglected in PLCA databases (Majeau-Bettez, 2011).

Mainly single region IO systems are chosen for IOLCA application as, depending on the underlying country, they have higher sectoral resolution and more impact indicators (Finnveden et al., 2009; Lenzen et al., 2013) than multi regional input-output (MRIO) databases. Exemplary the single region U.S. Bureau of Economic Analysis IO table has been used for different IOLCA purposes (Egilmez et al., 2014; Junnila, 2006; Majeau-Bettez, 2011). However, in contrast to MRIOs (e.g. Tukker and Dietzenbacher (2013)) single region IOs do not account for differences in sectoral production characteristics across countries (Voigt et al., 2014), nor is trade data accounted for, which holds relevant information for e.g. embodied emissions calculations (Cristea et al., 2012; Davis and Caldeira, 2010). In case of MRIO data, recently, new databases have been published (Tukker and Dietzenbacher (2013)) and new concepts aiming for highest possible detail and regular updates (Lenzen et al., 2013) have been installed. There have been promising approaches to consider further indicators (Ewing et al., 2012; Wiedmann et al., 2013).

Reducing possible weaknesses of IOLCA and PLCA, different HLCA methodologies have been developed (Egilmez et al., 2014; Finnveden et al., 2009; Lenzen and Crawford, 2009; Suh and Huppes, 2005). They combine both alternatives, using the high level of detail of PLCA, its End-of-Life- and Use phases impacts and the system completeness of IOLCA. Generally, it is assumed that HLCA causes smaller relative errors because errors related to aggregation, homogeneity, neglecting of sectors, End-of-Life phase, availability of impact categories or regional and sectoral resolution are reduced (Egilmez et al., 2014; Guinée, 2011; Majeau-Bettez, 2011; Rowley et al., 2009).

In this paper we develop a framework based on MRIO data, allowing to estimate overall environmental impacts related to production when adapting technological innovations considering the global economic network. Our analysis builds on the comparison of a conventional (reference) process i.e. one that is currently used in practice, with innovative alternatives. All processes are evaluated based on their requirements for direct inputs, enabling (P)LCA as well as evaluation within the developed MRIO-framework. After identifying conventional processes within the MRIO network, the impact of technological adaptation is assessed by replacing those by innovative alternatives and adjusting flow structures using third party data on related processes. The resulting changes - under the assumption of fixed final demands within the economic network - are then translated to specific assessment criteria, e.g. CO_2-emissions.

We exemplarily apply this methodology for two innovative manufacturing processes: longitudinal welding of large diameter steel pipes and turning of high-temperature resistant materials with an internally-cooled turning tool. For each process, three scenarios are conducted, in which reference processes are hypothetically replaced by innovative processes in Germany, Europe and across the globe, respectively. For demonstration purposes the application of this paper solely investigates changes in CO_2-emissions.

Results show that our framework allows for conclusions on overall emissions considering changes within the economic network. We find that for longitudinal welding and internally cooled turning processes innovative alternatives could contribute to overall emissions reduction.

We contrast our analysis by established PLCA (performed with GaBi process database (PE International, 2015)), IOLCA and HLCA, hence allowing for a comparison of the micro (process) with the macro (economy wide) perspective. We find that all methodologies identify the innovative welding technology to be environmentally beneficial, while in case of turning alternatives conclusions differ.

The paper is structured as follows: Section two describes the methodological foundations and gives an overview of recent MRIO databases. Section three introduces the considered process alternatives. In section four and five we give results for MRIO-based assessment methodology and LCAs, respectively. Section six concludes.

2. Process assessment using Multi-Regional-Input-Output data

This section describes the integration of process innovations into MRIO data as an approach to assess their macroeconomic impacts holistically.

2.1. Multi-Regional-Input-Output data

MRIO data approximates structures of the global production networks. Depending on the dataset it considers a characteristic set of r regions $R = \{r_1, \dots, r_n\}$ and s sectors $S = \{s_1, \dots, s_m\}$, that reflect all interactions throughout production allowing for an arbitrary trace back of production steps (Miller and Blair, 2009). As each dataset has individual R and S, as well as specific satellite data it serves for specific application. The current most prominent MRIO datasets are the World Input-Output Database (WIOD) (r=41, s=35) (Dietzenbacher et al., 2013), a dataset with focus on the European Union and its most important trading partners, EORA (Lenzen et al., 2013), a dataset with high resolution, combining available national IO data, thus having higher possible non-homogeneous sectoral resolution (r=187, s dependent), the OECD data based GRAM (Wiebe et al., 2012) (r=55,s=48) and Exiobase (Tukker et al., 2013), a dataset available for 2000 and 2007 with comparably high sectoral resolution (r=48,s=163) and many environmental satellite indicators (Wood et al., 2015). Furthermore, the Global Trade Analysis Project (GTAP) (Narayanan et al., 2012), a trade database, can be transferred to MRIO structure (Andrew and Peters, 2013; Peters et al., 2011) resulting in an economic network with 57 sectors and 140 regions in its latest version (Narayanan et al., 2015), considering a wide range of developing countries.

For our analysis we use GTAP 8.1 MRIO data primarily because it holds a comparably high (homogeneous) sectoral resolution for more than 130 countries. In contrast to (Peters et al., 2011), we use quantities at agents' prices throughout the construction process. This is done since relevant process data, transferred to monetary values, consider taxation.

2.2 Identification and implementation of processes

Due to the network characteristics of the MRIO model, changing any interaction of its sectors induces further adjustments in other sectors caused by mutual interlinkages ("higher-order effects"). In this study those changes result from the comparison of an innovative technology to a defined reference process. One characteristic of our approach is that total, static macroeconomic production network structures are considered and hence kept when evaluating changes, i.e. final demand is constant and delivery proportions are kept equal. We aim to hypothetically analyze CO_2 relevant effects of process innovations taking into account full product chains.

Each case study needs to be framed by defining a reference- and one or two innovative processes, where the reference process is a process that is representative for currently used technology that is to be replaced by the innovative process. Ideally, all process-relevant inputs and differences between the process alternatives (e.g. material, energy, human labor…) are known. Furthermore, when implementing the technological exchange additional questions have to be answered, regarding a) the extent to which the reference process is replaced and b) where the innovative process is applied.

As a second step, the reference processes need to be identified and located within the MRIO network. As the GTAP MRIO data depict inter-sectoral flows in monetary units, physical units (e.g. weight of the material or kWh of electricity) measured for the processes need to be converted to monetary units (e.g. USD/year). This is done by using representative average prices, including taxes and subsidies (i.e. agent's price)[1] for the corresponding year. To assess the total scope of the process, its absolute share on the region's sectoral economic input- and output flows has to be estimated ("How many times the process is applied annually in the considered region?"). This step might involve many assumptions as data might not be directly available and need to be estimated by appropriate workarounds. For integration in the MRIO network, the inputs and processes then need to be assigned to the (usually highly aggregated) MRIO sectors. This requires further assumptions about the origin of the respective input streams since not every process can be assigned unequivocally to one specific sector.

With the gained knowledge the reference processes can be replaced by innovative alternatives. Assuming constant final demands we obtain modifications in the interindustry matrix which enable to calculate changes considering higher order effects in

[1] Depending on the availability of detailed data (taxes and subsidies), an implementation in market prices would also be possible

subsequent steps that can be translated to CO_2-emissions. The procedure is given in mathematical detail in the next subsection, exemplary applications are provided in Section 3.

2.3 Mathematical foundation

In the following we will provide the most relevant notation; please see (Miller and Blair, 2009) additional mathematical details on MRIO modeling.
A MRIO dataset consists of an interindustry flow matrix, Z, accounting for flows re-entering production processes and a final demand matrix, Y, accounting for flows that enter consumption. Z is constructed in such a way that single entries reflect the sum of monetary flows from a region r_i, sector s_t to a region r_j, sector s_v, where $i, j \in n$ and $t, v \in m$, hence we denote those entries by Z_{it}^{jv}. Analogously, single flows entering the final demand are denoted by Y_{it}^{j}, representing all monetary flows from region r_i, sector s_t into region's r_j final demand.

By O, we denote the total output matrix, consisting of entries O_{it} which are gained by $O_{it} = \sum_j \sum_v Z_{it}^{jv}$. The regional sectoral input matrix I, with entries I_{jv} is obtained by $I_{jv} = \sum_i \sum_t Z_{it}^{jv}$.

Additionally, GTAP 8.1 provides satellite data on released CO_2-emissions. Let CO_2^{tot} denote the vector of length $n \times M$ whose entries CO_2^{it} denote total emissions released by sector s_t in region r_i . Dividing those by total sectoral outputs results in a vector that we denote by co_2^{tot}, which entries co_2^{it} reflect emissions associated to 1 USD of output.

With A we denote the technology matrix that consists of entries A_{it}^{jv}=Z_{it}^{jv}/O_{jv}, reflecting necessary inputs to produce one USD of sectoral output.

As an example a reference process is to be replaced in region r_j, sector s_v. With the knowledge on the sectoral share of the reference process, it is possible to calculate the modified technology matrix, which we denote by $A*$.
By dA we denote the matrix that transfers A (considering reference processes) into $A*$ and therefore reflects the technological exchange. By definition the following relation holds:

$$A - A^* = dA.$$

To assess the macroeconomic impact of technological change, considering interactions of production chains we utilize the Leontief inverses $L = (I - A)^{-1}$. The Leontief inverse accounts for all inputs that have been used for production, therefore the relation $O = LY$ holds (Miller and Blair, 2009). Consequently change in all sectoral outputs dO due to exchanged technology can be calculated by:

$$dO = O - O^* = LY - L^*Y = ((I - A)^{-1} - (I - A^*)^{-1})Y.$$

This relation can be translated to changes in CO_2-emissions:

$$dCO_2 = (O - O^*) \times co_2^{tot} = ((I - A)^{-1} - (I - A^*)^{-1})Y \times co_2^{tot},$$

whereby × denotes entry-wise multiplication.

Summing up, we can come up with a "recipe" for evaluating macroeconomic effects of single process innovations. The procedure is as follows:

1. Get Z, Y, O, co_2^{tot} from MRIO
2. Calculate A = Z / O
3. Investigate the innovative process with all its inputs
4. Find data on the amount of processes that need to be replaced within relevant sectors and calculate shares of relevant technologies as shares of sector and sectoral inputs
5. Derive the technology matrix for the innovative process A*(i,j)
6. Calculate $L = (I - A)^{-1}$ and $L^* = (I - A^*)^{-1}$
7. As final demand Y is assumed to be constant, calculate $O = LY$ and $O^* = L^*Y$
8. Multiply with CO_2-intensities and get changes in carbon emissions

The calculations for this study are run in Python (Python Software Foundation., 2014). We do not consider potential changes in price-, demand levels or substitutions, as their short-term influence is probably rather low for the considered case studies.

3. Case studies: process innovation technologies in welding and turning

This section introduces the processes alternatives for which environmental assessments are performed: i) welding of large-diameter steel pipes (Sproesser et al., 2015) (in the following indicated by subscript *w*) and ii) turning of high temperature resistant materials (Uhlmann et al., 2013) (indicated by subscript *t*). Both processes are found in comparatively small and highly specialized fields. In both cases it is an open question whether the innovative processes (indicated by *B*) provides improvement in environmental performance compared to the reference process (indicated by *A*).

For the sake of comparability and data availability, only Carbon-dioxide emissions are considered, although LCA can provide information on further impacts. Subsequently, the results from the developed MRIO framework are compared to results from LCA analyses.

3.1 Longitudinal welding of large-diameter steel pipes

Longitudinally welded pipes are used in the oil and gas industry. Pipeline manufacturing involves forming a metal plate into the shape of a ring and subsequently joining both plate ends by welding. Due to their vast dimension and wall thickness high power welding processes are applied. Among these, Submerged Arc Welding (SAW) is the most prevalent technology for large diameter pipe welding, in the following also referred to as process A_w. This is mostly because it offers both high deposition rates and welding speeds. In SAW an arc is formed between the work piece and a consumable electrode beneath a cover of granulated material called welding flux. Usually SAW is executed with multiple serial wires (multi-wire SAW) to further increase cost efficiency and process performance. Multi-wire SAW serves as the reference process for this study.

As representative components wall thickness of 25.4 mm (1 inch) and pipe outer diameter of 1016 mm (40 inch) are assumed. In Figure 1 the seam preparation and the welding sequence for the multi-wire SAW reference process (left side) are illustrated. Welding is performed in three phases. First the two plate ends are tack welded by Gas Metal Arc Welding which is followed by the first and second multi-wire SAW filler passes.

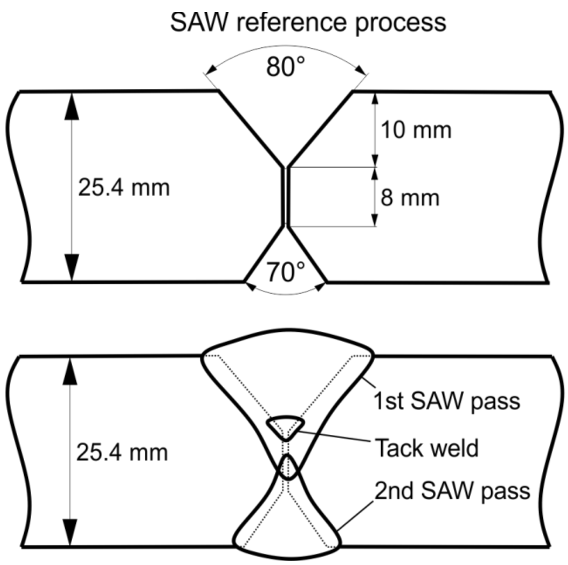


Figure 1: Seam preparation and welding sequence of process A_w (SAW) and process B_w (HLAW). In B_w, significant savings in welding material and electricity consumption are achieved.

Due to the product size and the process specific seam preparation multi-wire SAW consumes large amounts of material and energy. As an innovative approach Hybrid Laser Arc Welding (HLAW) and high power Tandem Gas Metal Arc Welding (TGMAW) are combined to reduce material as well as energy consumption, denoted by process B_w. HLAW combines Laser Arc Welding (LAW) and Gas Metal Arc Welding (GMAW). It has gained popularity because it benefits from the advantages of both technologies (Ribic et al., 2009). Additionally HLAW offers huge potentials for increasing economic and environmental performance when substituting or enhancing conventional arc processes (Chang et al., 2014; Gook et al., 2014; Sproesser et al., 2015). However, the maximum plate thickness for robust one pass welding is limited. Therefore TGMAW is selected to complete the weld. In contrast to the conventional single wire GMAW the tandem variant is able to weld with much higher speeds and deposition rates that are needed to compete with conventional processes like SAW (Lezzi and Costa, 2013; Morehead, 2003; Thompson, 2008). Furthermore in contrast to SAW, TGMAW performs on smaller grooves and has no need for removing slag or handling the welding flux. Weld seam preparation (top) as well as the welding sequence (bottom) are displayed in Figure 1 (right side). First the root gap width of 14 mm is tack welded (HLAW tack weld). Subsequently the weld is finished by two TGMAW filler passes.

Material, electricity, welding flux and shielding gas consumption per meter weld seam are considered as main process inputs for macroeconomic and microeconomic assessments. Material demand is determined by groove volume according to the seam preparation and steel density. Electricity consumption is calculated by the total power usage according to the used equipment and welding speeds. Electricity demand of HLAW covers the Laser and the GMAW power with wall-plug efficiencies of 30 % and 80 % as well as additional consumption for the cooling unit (Haelsig, 2014; IPG Phtotonics, 2015; Vollertsen et al., 2010). Electricity consumption of TGMAW and multi-wire SAW is calculated by the respective voltages and currents and the wall-plug efficiency of 80 %. Shielding gas demand is obtained by the flow rate and welding speed. Welding flux consumption is taken from literature sources and material data sheets (ESAB GmbH, 2015; Müller and Wolff, 1983). Needed inputs per meter weld seam are listed in Table 1.

Table 1: Resource input per [m] of welded pipe for welding processes A_w and B_w

		Process A_w (SAW process)	**Process B_w (HLAW process)**
Wire	[g]	1096.28	211.29
inert gas	[$ltr_{1\ bar}$]	12.50	34.36
electricity consumption	[kWh]	2.94	1.02
welding flux powder	[kg]	1.32	0

3.2 Machining with internally-cooled turning tools

As a second exemplary process, the machining of high temperature resistant materials, e.g. titanium alloys or nickel-base alloys, is considered. As very high cutting forces apply those processes are energy-intense. Conventionally, titanium alloys are machined with cemented tungsten carbide tools that are cooled with a cooling lubricant by flood cooling, in the following also referred to as process A_t, “wet machining”. Analogously, machining without any external cooling lubricant is labeled as “dry machining” in the following. 15 to 35 % of the machine tool’s total energy consumption is spend on the provision of the external cooling lubricant to the cutting zone where an even temperature level needs to be maintained (Klocke and Eisenblatter, 1997; Uhlmann et al., 2013). In the following, mainly the turning process is considered, although the technology is also applicable to other types of cutting processes.

The energy consumption that is caused by the cooling system can be reduced by using cutting tools with integrated closed loop cooling systems (“internally-cooled tool”, ICT).

A new type of turning tool has been developed to decrease thermal losses (Figure 2). A glycol-water mixture is used as coolant.

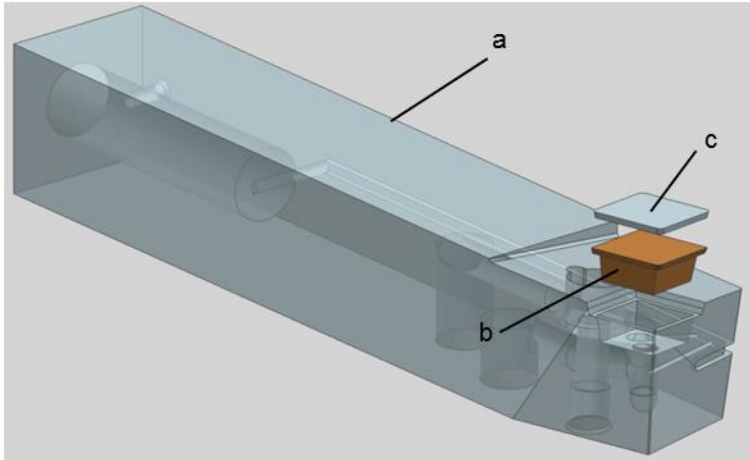


Figure 2: Architecture of Digital Mock Up (DMU) of prototypical evo.T^4 tool holder with integrated closed-loop cooling system.
a) insert holder; b) micro cooling system; c) cutting insert

Turning experiments with and without the provision of cooling lubricants in combination with the internally-cooled tool were undertaken to investigate energy consumption and tool wear in the respective process combinations (processes B_{1t} and B_{2t}). The degree of efficiency with regard to the cooling method is determined by calculating the specific energy consumption of the tool wear, the main spindle and the feed drives. The data is acquired by combining the evo.T^4 tool[2] with a power measurement system. This enables process-parallel data acquisition of energy flows and the calculation of the process efficiency. The data is used to determine the highest productivity considering minimized energy consumption and tool wear. The evo.T^4 tool has been produced by selective laser melting to embed fluid and sensor channels into the holder and to decrease the amount of tool material. A high performance heat sink made of a copper alloy is used to cool the insert. Turning experiments are carried out with the CNC lathe TRAUB TNX 65, the internally cooled turning tool and the cooling and control system. TiAl6V4 is chosen as workpiece material. The experiments are undertaken with fixed cutting parameters to measure the effect regarding tool wear and energy consumption.

When analyzing the energy consumption of the different cooling methods, we observe dry machining without any cooling system to imply the lowest energy consumption of 5.7 kWh. However, the tool wear of the cutting insert is extremely high, caused by the so-called diffusion wear which is typical for turning of high temperature resistant materials. For this reason the dry-machining process without internal cooling is not further considered in the following case studies. In comparison to dry machining, turning with the internally-cooled turning tool, process B_{1t}, increases the energy consumption slightly due to the cooling liquid pump and chiller by 0.4 kWh (Figure 3). The highest total

[2] Nomenclature: **Evo** evolution, **T** tool system, **C** cooling system, **1**/**2**/**3**/**4**/**5**: technology readiness level. (Evo.T4: machine tool is suitable for technology demonstration)

energy consumption of 8.0 kWh is caused by flood cooling due to the high energy demand of the cooling lubricant pumps and chiller, combined wet and internally-cooled turning, process B_{2t}. Cooling the insert internally and externally limits the rise of temperature and thus decreases the wash out effect of tool material due to the contact between tool and workpiece material.

When analyzing the tool wear of the different cooling methods, it becomes obvious that dry machining causes the highest tool wear rates, while wet machining in combination with the internally-cooled tool (process B_{2t}) shows the lowest tool wear rates (see Figure 3).

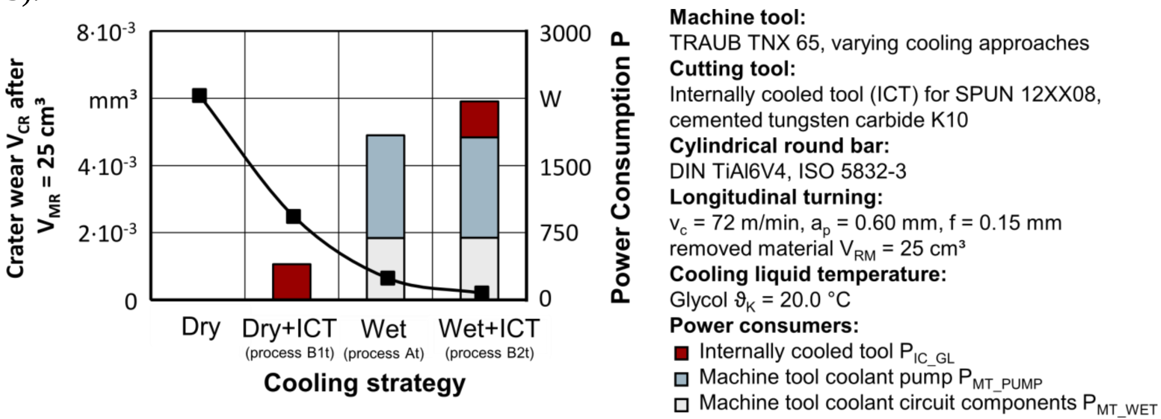


Figure 3: Energy consumption and tool wear for different cooling processes, own experiments and visualization.

2.2 kWh are used by pump, the cooling lubricant chiller and the coolant circuit components in total when applying wet machining. Comparing the process alternatives under those assumptions, dry machining with the internally-cooled tool, process B_{1t}, leads to the lowest energy consumption. However, this approach does neither consider the production process of further inputs such as cooling liquids, nor higher-order stages of the production. Input factors per reference unit are shown in Table 2.

Table 2: Needed inputs per reference unit and per [t] TiAl6V4 for implemented turning process.

		Process A_t (wet machining)		**Process B_{1t} (dry machining & internally-cooled)**		**Process B_{2t} (wet machining & Internally-cooled)**	
		per unit (0.6037 kg raw material input)	**per t of input (TiAl6V4)**	**per unit (0.6037 kg raw material input)**	**per t of input (TiAl6V4)**	**per unit (0.6037 kg raw material input)**	**per t of input (TiAl6V4)**
Electricity	[kWh]	2.0	3,312.8	1.6	2,584.0	2.2	3,561.3
Cooling lubricant: emulsion	[ml]	6.0	9,938.5	-	-	6.0	9,938.5
Coolant: Glykosol	[ml]	-	-	0.4	662.6	0.4	662.6

machine tool: cutting insert	[insert unit = 2.5 g]	1.0	1,656.4	4.2	6,907.3	0.4	579.7

4. Technology assessment using the MRIO approach

Based on the process data it is possible to investigate macroeconomic CO_2-emission reduction potentials using the MRIO framework. An additional simplification is made for the sake of comprehensibility: Although GTAP 8.1 differentiates 134 regions, we chose to aggregate the system to two regions ("considered region" and "rest of world"). This means that input streams can only be either "domestic" or "imported". In case of imported goods, no further assumptions are made. Each process innovation is evaluated in three scenarios, in which it is assumed that the innovative process completely replaces reference processes within i) Germany, ii) Europe and iii) globally respectively.

4.1 MRIO process replacement results for welding

Investigating the welding processes, we regard the SAW process as conventional reference process A_w. The innovative HLAW process (process B_w) is characterized by significantly lower consumption of electricity, wire and flux powder compared to A_w. Otherwise, the inert gas consumption increases (see section 3.1, Table 1).

For assessing the magnitude of possible effects on global CO_2-emissions reliable data on the overall scope of the process are indispensable. Ideally, this includes information on the total cumulated length of weld seam of longitudinal seam-welded large-diameter pipes. We approximate data that are not directly available in the following way. According to statistical data from German Steel Tube Association (2014), 356,000 tons of large-diameter steel pipes have been produced in Germany in 2013, of which 50% are assumed to be within the plate thickness range. Assuming an average outer diameter of 1.02 m and an average plate thickness of 0.0254[3] m, the cumulated weld seam length can thus be estimated to be 571.2 km/year (steel density: 7.85 t/m³). The total length is used for identifying and replacing the reference process in the MRIO network. As functional unit we use 1m of weld seem.

Since GTAP uses monetary flows, the prices for the process inputs were collected from manufacturer information, statistical databases and surveys among established equipment suppliers (ESAB GmbH, 2015; Statistisches Bundesamt, 2014a; The Linde Group, 2015), results are shown in Table 3, all costs include taxes.

Table 3: Price overview of inputs per reference unit for both welding processes. All prices are normalized to 2004 USD. The numbers in brackets indicate the years of original price data. With the exception of electricity, no historic data have been available.

Inputs		Process A_w	Process B_w

[3] based on trade data and own estimations.

1	Wire (2014)	[USD/kg]	2.636	2.636
2	inert gas: corgon (A), CO_2 (B), (2014)	[USD/ltr_{1bar}]	0.001	0.004
3	electricity consumption (2007)	[USD/kWh]	0.105	0.105
4	welding flux powder (2014)	[USD/kg]	2.109	-

The process inputs are translated to monetary flows and then scaled up to the German iron and steel industry sector. To integrate the price data within the GTAP 8.1 database, which provides data for 2007 given in USD 2004, data need to be transferred to USD 2004. With the exception of electricity, historic price data are not directly available, since costs given in Table 3 refer to specific processes and base on supplier estimations that strongly depend on purchase quantity, project size etc., we approximate 2004 prices by using German national inflation rates between 2004 and 2014 (World Bank, 2015) and the 2004 average EUR/USD-exchange rate for currency conversion (European Central Bank, 2015). Thus the input differences of process alternatives can be transferred and assigned to corresponding GTAP 8.1 sectors (see Table 4).

The inputs are further distinguished in “imported” and “domestic”. We allocate those inputs in accordance with the overall sectoral import/export ratio. That means if 10 per cent of fabricated metal products (FMP) that flow into the “Iron & Steel” sector (I_S) are produced domestically it is assumed that this ratio also holds for each subproduct of the FMP sector such as wire or welding flux powder.

By considering the input differences between process alternatives and monetary values, the first order changes within the economic system can be calculated (**Fehler! Verweisquelle konnte nicht gefunden werden.**4), and be considered in the MRIO-replacement framework to calculate A^* (see Section 2).

Table 4: Monetary changes in input flow into the iron and steel sector caused by exchanging welding process A_w by B_w for Germany. The process and its inputs are assigned to suitable sectors within GTAP 8.1; see full sector names in Appendix. All costs are in 2004 USD.

	Direct input change in Mio. $	GTAP 8.1 Sectors
Wire	-1.332	FMP → I_S
inert gas: corgon (A), CO_2 (B)	0.07	CRP → I_S
electricity consumption	-0.115	ELY → I_S
welding flux powder	-1.584	FMP → I_S

The results show that overall impacts are small, which is not surprising as a niche process innovation within the global economy is considered. Nevertheless, the technology exchange can be held accountable for measurable overall impacts: the CO_2-emissions, considering upstream layers decline by 1.5 kt (see Table 5). It can therefore be concluded that savings due to electricity and wire consumption outweigh higher demand for inert gases.

When extending the case study towards the European or global pipe production a main obstacle is the availability of average global price data. We approximate the European and global impact by assuming that the relative size (share) of input changes within the specific sectors remains constant. This assumption is not necessarily realistic as the economic structure certainly varies between countries, but it can provide plausible orders of magnitudes of the results. More exact approaches would depend on the availability of better data.

If the reference process was replaced by the innovative process within Europe, a CO_2-emission reduction of 24.5 kt/a could be achieved and a reduction of 120.1 kt/a in case of global replacement (Table 5). It is notable that the emission reductions increases more than proportionally compared to cost reduction when technology application is extended (134.4 Mio. USD compared to 302.3 Mio. USD). This behavior can be caused by higher carbon intensities of the electricity production in non-European countries.

Table 5: Results if process B_w replaces reference process A_w in Germany, Europe and globally, respectively. Results show carbon emissions reductions in kt (lower row) as well as changes in costs USD 2004 (upper row).

Innovative process B_w applied in:		**GERMANY**	**EUROPE**	**WORLD**
Global impact	in Mio. USD 2004	- 6.7	-134.4	-302.3
	in %	$-0.01 \cdot 10^{-3}$	$-0.24 \cdot 10^{-3}$	$-0.54 \cdot 10^{-3}$
	in kt CO_2	-1.5	-24.5	- 120.1
	in %	$-0.01 \cdot 10^{-3}$	$-0.11 \cdot 10^{-3}$	$-0.53 \cdot 10^{-3}$

4.2 MRIO results of the turning process

Processing TiAl6V4 is increasingly applied in aviation manufacturing (MAKINO Machine Tools, 2014). We therefore focus our study on turning processes on civil aviation sectors, where turning technology for TiAl6V4 will hypothetically be replaced. As some necessary data are not directly available, assumptions have to be made.

For the turning process three alternatives are considered (see section 3.2): the reference process A_t (wet machining) and the innovative processes B_{1t} and B_{2t} that include an internally cooling system with and without additional wet machining, respectively.

The input data on TiA16V4 turning are obtained from data collected during production of the heat shield of a helicopter turbine, which is used as functional unit for the following calculations. The production of one reference unit requires 0.6037 kg of semi-manufactured TiAl6V4 as well as electricity, chemicals and machine tools in the quantities shown in Table 2.

We use two approaches to estimate the total amount of turned TiA16V4: Firstly, the import data of titanium pre-products and secondly, the titanium content of the civil

Airbus aircrafts which are assumed to account for a significant share of the civil aviation sector. Both approaches do not provide precise numbers, but indicate the magnitude of total turned TiAl6V4.

The import approach builds on the assumption that most of the titanium processed in the civil aviation sector is imported in semi-manufactured form (plates, bars etc.) as Germany has no titanium mining. In 2012, 6619.20 t of titanium pre-products have been imported (Statistisches Bundesamt, 2014b). However, the statistics do not provide information in which sectors the pre-products are further processed. Since only the aviation sector is of interest, we further assume that an estimated maximum of 50% of the imports (3309.6 t) is further processed for civil aviation. Our estimated maximal amount corresponds to about 10% of total titanium mass processed by Airbus for delivered civil aircrafts in 2014 (underlying assumption: 70% of material waste during processing) (Airbus S.A.S., 2014). As a high share of Airbus production is not located in Germany this number appears to be reasonable. The process inputs are calculated based on unit prices given in Table 6. The electricity price for industrial users is obtained from Statistisches Bundesamt (2014a), other price data are derived from our experience values. Analogously to the welding case study (Section 4.1) prices are transferred to 2004 values and converted to USD to match the GTAP 8.1 MRIO database. After calculating the input differences provided by different technologies and assigning them to the respective GTAP sectors, see Table 7, the implementation is run.

Table 6: Costs of input units (2014) for turning process. All prices are given in 2004 USD. Numbers in brackets indicate the year of the original price data. With the exception of electricity no historic data has been available.

		Process A_t (wet machining)	**Processes B_{1t} & B_{2t} (internally-cooled, dry & wet machining)**
Electricity (2007)	[USD/kWh]	0.105	0.105
Cooling lubricant: emulsion (2014)	[USD/ltr]	5.810	5.810
Coolant: Glykosol (2014)	[USD/ltr]	2.324	2.324
Machine tool: cutting insert (2014)	[USD/insert unit]	9.876	6.971

Table 7: Monetary flow differences caused by changes in the turning process for Germany. The process and its inputs are assigned to suitable sectors within the GTAP 8.1 database; see full sector names in Appendix. All monetary values are given in USD 2004.

	Direct input change in Mio. $, A_t-B_{1t}	**Direct input change in Mio. $, A_t-B_{2t}**	**GTAP 8.1 Sectors**
Electricity	- 0.25	0.09	ELY → FMP
Cooling lubricant: emulsion	- 0.17	0	CRP → FMP
Coolant: Glykosol	<0.01	<0.01	CRP → FMP
Machine tool: cutting insert	95.48	- 36.99	FMP → FMP

Results for the environmental impacts of process innovation are shown in Tables 4 and 5. When replacement takes place in Germany only, global CO_2-emissions decrease by 14.9 kt/year for process B_{2t}, but increase by 38.3 kt/year for process B_{1t}. Therefore, within the framework it can be concluded that only process B_{2t} leads to improvements in terms of cost efficiency and carbon emissions, while process B_{1t} increases both. This result is particularly relevant since it cannot be derived directly from the data shown in Table 7, as it considers changes in upstream supply chains, as well as changes in the Leontief inverse.

Extending the regional scope to Europe (World), analogous to Section 4.1, leads to a hypothetical reduction of CO_2-emissions of 52.1 kt (169.7 kt) (Table 8) for process B_{2t} and increases by 133.4 kt and 431.8 kt for process B_{1t}, respectively (Table 9).

Table 8: Results for the turning process B_{1t} for process implementation in Germany, Europe and the World. All monetary units are in USD 2004.

Innovative process B_{1t} applied		**GERMANY**	**EUROPE**	**WORLD**
Global impact	in Mio. USD 2004	+ 218.0	+ 843.8	+ 1788.6
	in %	$+ 0.39\cdot10^{-3}$	$+ 1.51\cdot10^{-3}$	$+ 3.20\cdot10^{-3}$
	in kt CO_2	+ 38.3	+ 133.4	+ 431.8
	in %	$+ 0.17\cdot10^{-3}$	$+ 0.59\cdot10^{-3}$	$+ 1.89\cdot10^{-3}$

Table 9: Results for the turning process B_{2t} for process implementation in Germany, Europe and the World. All monetary units are given in USD 2004.

Innovative process B_{2t} applied		**GERMANY**	**EUROPE**	**WORLD**
Global impact	in Mio. USD 2004	- 84.6	- 327.8	- 696.4
	in %	$- 0.15\cdot10^{-3}$	$- 0.59\cdot10^{-3}$	$- 1.24\cdot10^{-3}$
	in kt CO_2	-14.9	-52.1	-169.7
	in %	$- 0.07\cdot10^{-3}$	$- 0.23\cdot10^{-3}$	$- 0.74\cdot10^{-3}$

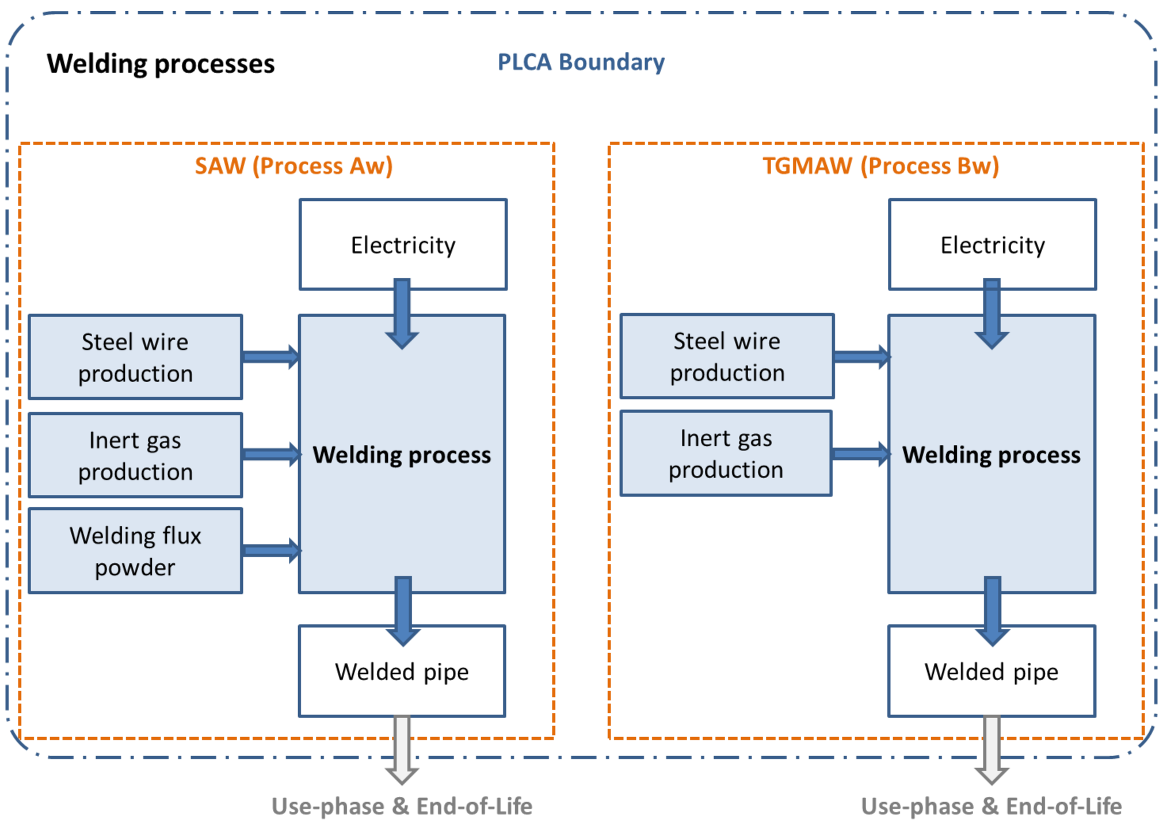
5. Technology assessment using (P)LCA

In this section we evaluate results of PLCA studies for both processes. The PLCA studies are carried out using the software tool GaBi 6.0 (PE International, 2015), the system boundaries are chosen as shown in Figures 4 and 6.
As functional units 1m of seam weld and turning of one heat shield of a helicopter turbine are chosen. Within the PLCA only cradle to gate impacts are modelled, for the sake of comparability, as the End-of-Life- and Use phase cannot be modelled within MRIOs. Furthermore results of IOLCA and HLCA are given.

5.1 PLCA results of the welding alternatives

LCA methods enable an alternative approach to investigate CO_2-emissions[4] (IPCC, 2014a) of the welding processes A_w and B_w (section 3.1). The assessment includes upstream processes which are listed in Table SI 1 in the Appendix.

Figure 4 shows the PLCA purposes the following system boundary that is selected for welding processes.



[4] Within LCA characterization, Global Warming Potentials (GWP) are used to measure environmental burdens for a broad range of Greenhouse gases other than CO_2. Using GWPs of different GHGs, like CH_4, N_2O; their environmental impact can be measured in CO_2-equivalents, results are given in Appendix.

Figure 4: System boundary selection for PLCA analyses for welding processes considered in this paper: Submerged Arc Welding (SAW, left) and Tandem Gas Metal Arc Welding (TGMAW, right). For sake of comparability Use- and End-of-Life phase are excluded.

The inventory data of the inputs are identical to the data used in the MRIO analysis (Table 1). The chemical composition of the flux powder (Al_2O_3, CaO, MnO, MgO, CaF_2, SiO_2, TiO_2) are taken from product data sheets (Bavaria Schweisstechnik, 2015).

Results show that CO_2-emissions of the innovative process B_w are 81% lower than for the reference process A_w due to significant savings in material and electricity (see Table 10). The emission impacts of both processes are mainly caused by the production of steel wire and needed electricity: The steel wire accounts for about 40% of the total CO_2-emissions in both processes; the electricity consumption represents 56% and 30% of the total emissions in B_w and A_w process, respectively. In the reference process the welding flux powder consumption is significant as it accounts for about 30% of the CO_2- emissions. The impacts of inert gas and compressed air production are comparatively small.

Considering other GHGs indicates that those are of minor relevance (see Appendix Table SI 4), hence they are not further discussed here. Investigating IOLCA and HLCA results for GTAP 8.1 and Exiobase, see Figure 5, reveals that all alternatives judge the innovative process to be preferable. Furthermore, Exiobase results capture more CO_2-emissions than GTAP. In all cases HLCA and IOLCA results exceed those of PLCA, underlying that relevant emission shares (up to 6 kg) could be missed due to system incompleteness (truncation errors) or due to other reasons stated in the introduction.

Table 10: PLCA results: CO_2-emissions in kg for reference unit for different welding alternatives by using GaBi.

Process	Shielding gas	Electricity	Compressed air	Steel wire filler	Flux powder	Total
Bw (CO_2-emissions)	0.0182	0.6052	0.0166	0.4282	0.0000	1.0682
A_w (CO_2-emissions)	0.0096	1.7324	0.0000	2.2431	1.6886	5.6737

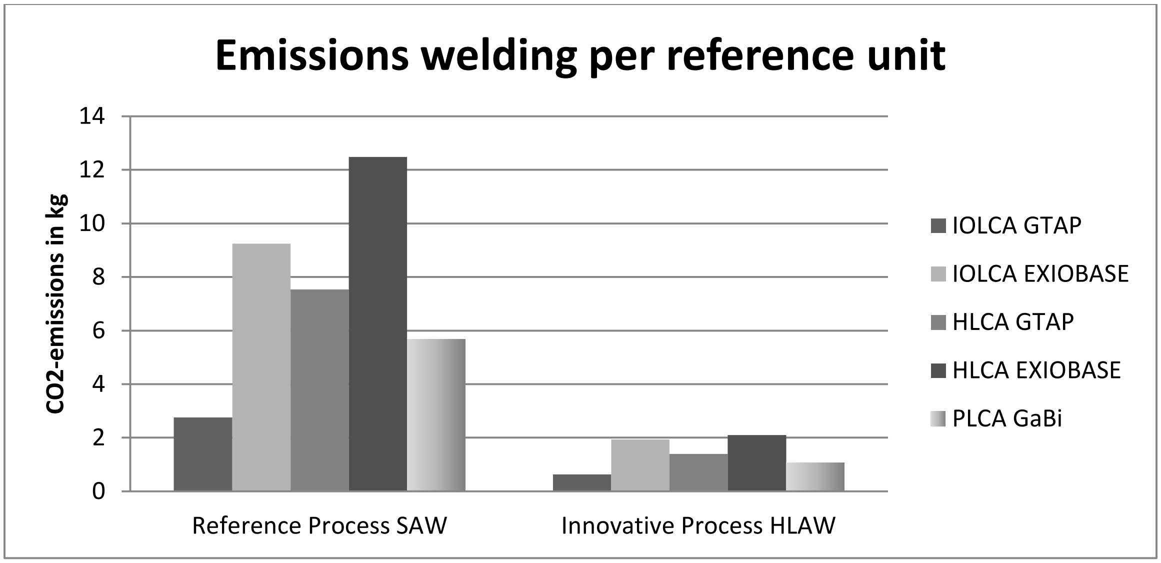


Figure 5: CO_2-emissions of IOLCA, PLCA and HLCA for welding processes alternatives.

5.2 PLCA results of turning alternatives

Additionally, the three types of turning technologies are assessed within PLCA[5], IOLCA and HLCA.

[5] PLCA process inventory is shown in Table SI 2 in the Appendix

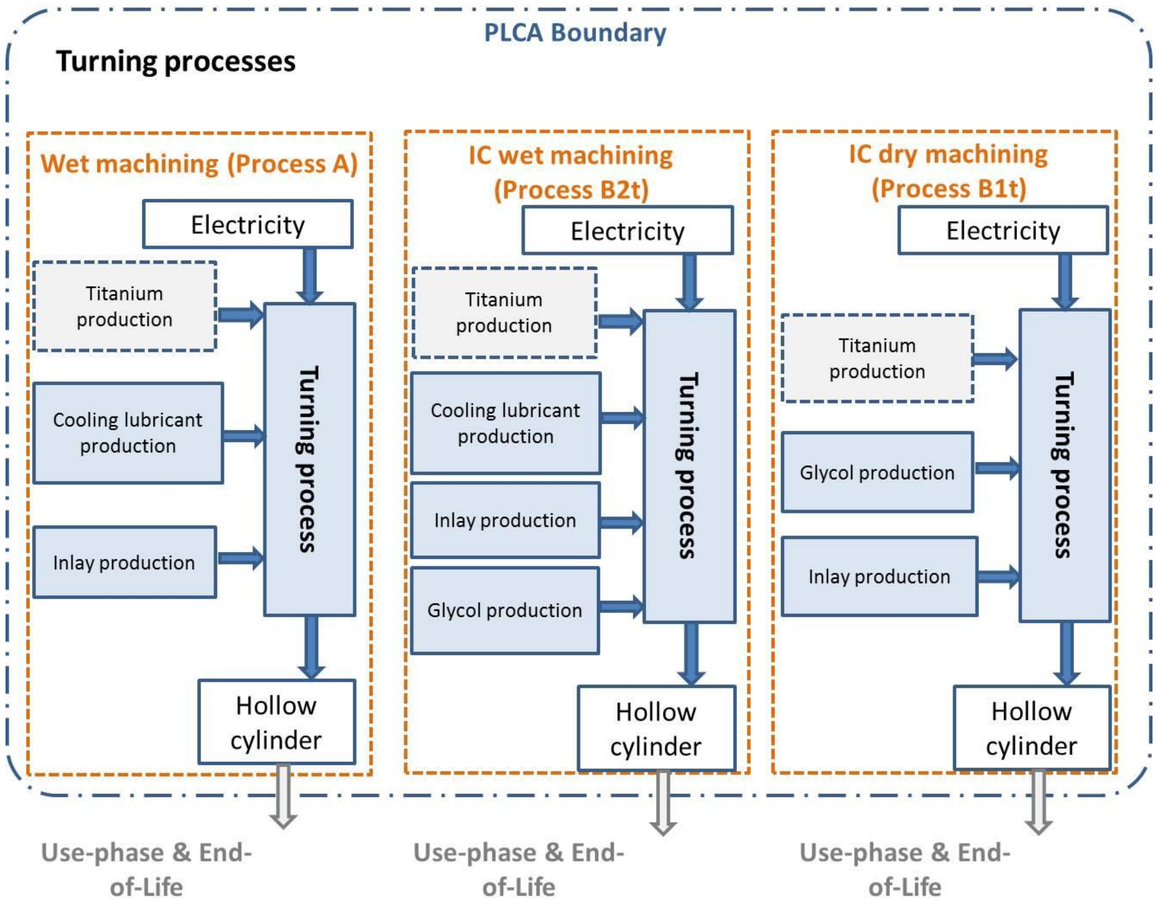


Figure 6: System boundary selection for PLCA analyses for turning processes considered in this paper: wet machining (Process A, left), internally-cooled (IC) dry machining (process B1t, right) and a combination of both, internally-cooled wet machining (process B2t, middle). For sake of comparability Use- and End-of-Life phase are excluded.

PLCA-results show that raw titanium clearly dominates the environmental profile of all three processes, as 8.89 kg of CO_2-emissions caused by titanium, compared to 1.24 kg of all other inputs combined. However, since the titanium consumption is not influenced by changing the turning technology, it is more meaningful to focus on the varying input differences. It can then be observed that the CO_2-emissions of the processes are mostly driven by the electricity needed, followed by the cutting insert production (see Table 11), for CO_2-equivalents see Table SI 3 in the Appendix.

Comparing PLCA CO_2-emissions, it becomes evident that process A_t performs best. Savings in electricity for IC dry machining (B_{1t}) compared to A_t are outweighed by a higher need for cutting inserts. The process IC wet machining (B_{2t}) reveals to have emissions savings concerning the cutting insert, which is outweighed by the emissions related to higher energy consumption, leading to slightly increased overall emissions.

Table 11: CO_2-emissions for turning process alternatives per functional unit. Absolute numbers are almost identical for all processes. The production of titanium has the highest contribution to total

emissions, but since this parameter remains unchanged in all process alternatives, it is not further considered (analogous for HLCA and IOLCA methodology).

	CO_2-emissions
Wet machining total (without Titanium):	**1.24**
Cutting insert production	0.09
Cooling lubricant production	0.01
Electricity in turning process	1.14
+ Titanium (constant for all processes)	8.89
IC dry machining total (without Titanium):	**1.25**
Cutting insert production	0.36
Cooling lubricant production	0.00
Electricity in turning process	0.89
+ Titanium (constant for all processes)	8.89
IC wet machining total (without Titanium):	**1.27**
Cutting insert production	0.03
Cooling lubricant production	0.01
Electricity in turning process	1.22
+ Titanium (constant for all processes)	8.89

Comparing PLCA with HLCA and IOLCA results reveals that for specifications in Figure 7 B_{2t} shows to have smallest impacts. In contrast alternative B_{1t} performs worst. Furthermore for all process alternatives HLCA and IOLCA reveal significant higher emissions per reference unit than PLCA. This could be caused by reasons discussed in the introduction. If HLCA results are correct, truncation errors caused by system incompleteness in PLCA could be up to 13 kg CO_2 in case of B_{1t}.

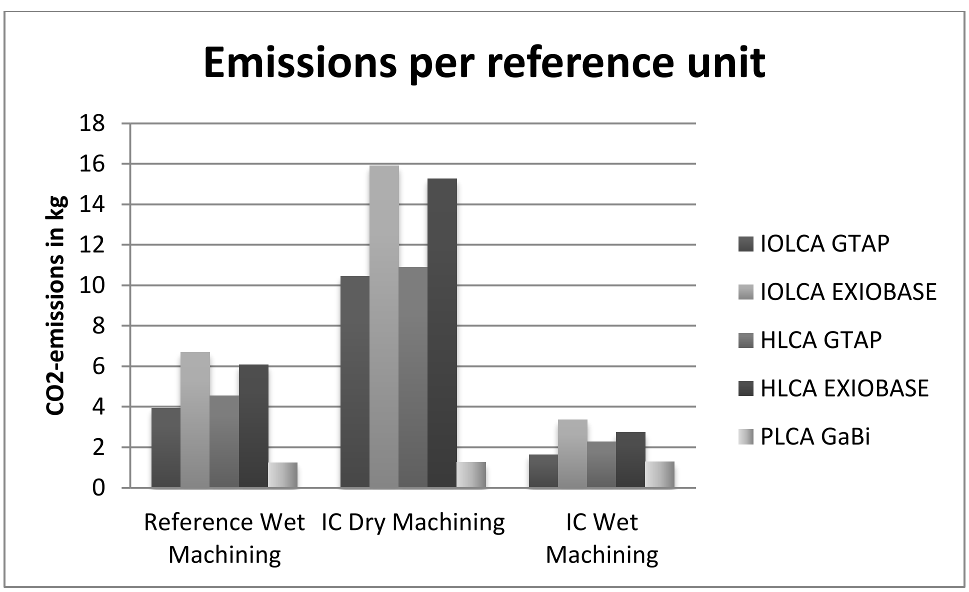


Figure 7: CO_2-emissions results of IOLCA, PLCA and HLCA for turning process alternatives, neglecting titanium production. All alternatives find that IC wet machining causes smallest CO_2-emissions.

6. Discussion and conclusion

In this paper we develop a MRIO-based framework and exemplarily demonstrate how to assess overall environmental impacts of innovative processes alternatives. We further give and compare results with information derived from established LCA analysis at the microeconomic level.
Our results demonstrate the value added of integrating process innovations into global production networks. Conclusions at the macroeconomic level are possible, which can especially help decision makers to understand the broader picture when considering specific process innovations and allow to set priorities for promoting new technologies.

Results among assessment methods differ, which is due to issues discussed in the introduction. For the welding study all methods suggest the innovative process to be environmentally favorable. In the case of turning PLCA favors the reference process. The MRIO upscaling framework considering the global production network shows improvements by alternative B_{2t} regarding global emissions, which is in line with HLCA and IOLCA. The MRIO framework results confirm that internally-cooled wet machining (B_{2t}) applied in the German aviation sector could decrease global emissions by 14.9 kt.
When relying on LCA only, it is important to note that a solely process-oriented view might fail to set the results into the context of the total economy. By ignoring macroeconomic infrastructures, the impact resulting from industrial dynamics are potentially neglected (Finkbeiner et al., 2014; Lenzen, 2000). Even if the total amount of processes was known, multiplying the PLCA/IOLCA/HLCA impacts by the amount of processes would not reflect characteristics of the economic network and macroeconomic changes in sectors. Here we would like to stress that a relevant change (relevant size) in production technology causes changes in the interindustry flow matrix and therefore necessarily the Leontief inverse, which is used for IOLCA and HLCA calculation. In the same vein a relevant technology adaptation would change representative processes contained in process databases as Ecoinvent or GaBi.

This issue becomes particularly evident when considering the following calculation. GTAP IOLCA and the MRIO framework consider the same underlying system making them comparable. Multiplying GTAP IOLCA welding CO_2-reductions by the total amount of yearly welded seam results in reductions of 1.2 kt, wherelse annual reductions are 25% higher by the MRIO framework. Those differences will further increase, if more relevant processes are investigated.

Even though all assessment alternatives aim to incorporate the carbon emissions holistically, they differ significantly concerning their system characteristics and underlying assumptions, as discussed in the introduction. It is further important to mention that methodologies used for our analysis need a large set of specific assumptions (see Sections 3 and 4), due to a lack of specific data. Changes in emissions should hence not be understood as final values, but rather indicate magnitudes and directions of possible impacts, which is even more important when considering the high level of aggregation within IO databases.

As stated in the introduction we only investigate impacts on CO_2-emissions. For a holistic sustainability assessment a broad range of sustainability dimensions needs to be considered (Finnveden et al., 2009). For example, regarding the turning-processes an internally-cooled system does not require the use of cooling liquids, which are potentially toxic and hazardous for the environment and human health and can thus contribute to improvements. Recent triple bottom line LCAs underlined the importance of simultaneously evaluating multiple impact categories, considering social, economic and ecologic impacts, when talking on sustainability issues (Onat et al., 2014). A triple bottom line LCA comparing performances of economic sectors across countries within MRIO models would be possible and can be done by further research, but having the disadvantage that accounting quality within regions varies. Further implications by homogeneity assumption would need to be taken into account.
Nevertheless, considering all relevant factors is thus far not possible in full detail relying on MRIO data, due to data availability even though availability is increasing (Finnveden et al., 2009). This underlines the necessity to consider process databases, when bearing in mind the already discussed complementary weaknesses.

We conclude that with the developed MRIO framework it is possible to quantify impacts at macroeconomic level holistically, as changes in economic structures can be accounted for (changed Leontief inverse) and therefore our methodology provides relevant value added in addition to existing LCA methodologies. We believe that with future improvements in MRIO datasets the methodology becomes more applicable, as resolution and impact factors will increase.

Up to then HLCA will be indispensable in future assessment making, minimizing errors caused by uncertainty, system boundary issues (Suh et al., 2004) or detail availability (Guinée, 2011).

Acknowledgments

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Appendix

List of Abbreviations

CRP	Chemical, rubber, plastic products (sector in GTAP 8.1 database)
ELY	Electricity (sector in GTAP 8.1 database)
FMP	Metal products (sector in GTAP 8.1 database)
GWP	Global Warming Potential
HLAW	Hybrid Laser Arc Welding
I_S	Ferrous metals (sector in GTAP 8.1 database)
IC	Internally-cooled
ICT	Internally-cooled tool
LCA	Life Cycle Assessment
MRIO	Multi-Regional Input Output
SAW	Submerged Arc Welding
TGMAW	Tandem Gas Metal Arc Welding

Table SI 1: Process and product inventory of GaBi used for PLCA analysis of welding alternatives.

Process steps	SAW (Aw)	TGMAW (Bw)
Base material	Structural steel S960	Structural steel S960
Wire	Steel wire	Steel wire
Inert gas production	Carbon dioxide	Argon
	-	Carbon dioxide
Welding flux powder	Silicon dioxide	-
	Titanium dioxide	-
	Aluminium oxide	-
	Manganese oxide	-
	Calcium oxide	-
	Magnesium oxide	-
	Calcium difluoride	-
Electricity	Electricity grid mix	Electricity grid mix

Table SI 2: Process and product inventory of GaBi used for PLCA analysis of turning alternatives.

Process steps	Wet machining (A)	IC dry machining (B1t)
Titanium production	TiAl6V4 alloy	TiAl6V4 alloy
Inlay production	Tungsten carbide	Tungsten carbide
	Cobalt	Cobalt
	Paraffin	Paraffin
	Process water	Process water
	Milling process	Milling process
	Spray-drying process	Spray-drying process
	Sinter process	Sinter process
	Electricity grid mix	Electricity grid mix
	Transport processes	Transport processes
Cooling lubricant production/Glycol	Phenoxyethanol	Ethylene glycol
	Naphtha	Process water
	Potassium	
	Petrochemical	
	Process water	
Electricity	Electricity grid mix	Electricity grid mix

Table SI 3 CO_2- and equivalent emissions of the turning processes.

	CO_2-equivalent	CO_2-emissions
Wet machining total (without Titanium):	**1.29**	**1.24**
Cutting insert production	0.10	0.09
Cooling lubricant production	0.01	0.01
Electricity in turning process	1.19	1.14
+ Titanium (constant for all processes)	9.51	8.89
IC dry machining total (without Titanium):	**1.31**	**1.25**
Cutting insert production	0.39	0.36
Cooling lubricant production	0.00	0.00
Electricity in turning process	0.93	0.89
+ Titanium (constant for all processes)	9.51	8.89
IC wet machining total (without Titanium):	**1.32**	**1.27**
Cutting insert production	0.03	0.03
Cooling lubricant production	0.01	0.01
Electricity in turning process	1.27	1.22
+ Titanium (constant for all processes)	9.51	8.89

Table SI 4 CO_2- and equivalents emissions of the welding processes.

Process	Shielding gas	Electricity	Compressed air	Steel wire filler	Flux powder	Total
Bw (CO2 equivalent)	0.0194	0.6242	0.0174	0.4536	0.0000	1.1146
Bw (CO2 emission)	0.0182	0.6052	0.0166	0.4282	0.0000	1.0682

Aw (CO2 equivalent)	0.0110	1.7870	0.0000	2.3759	1.7792	5.9530
Aw (CO2 emission)	0.0096	1.7324	0.0000	2.2431	1.6886	5.6737

Table SI 5: Monetary inputs in USD per reference unit for welding alternatives.

Inputs			Process A_w	Process B_w
1	Wire (2014)	[USD/reference unit]	2.89	0.557
2	inert gas: corgon (A), CO_2 (B), (2014)	[USD/reference unit]	0.013	0.137
3	electricity consumption (2007)	[USD/reference unit]	0.309	0.107
4	welding flux powder (2014)	[USD/reference unit]	2.784	-

Table SI 6: CO_2-emissions in kg per USD input.

Inputs		Process A_w	Process B_w
1	Wire (2014)	0.77	0.77
2	inert gas: corgon (A), CO_2 (B), (2014)	0.74	0.25
3	electricity consumption (2007)	5.6	5.6
4	welding flux powder (2014)	0.61	-

Table SI 7: Monetary inputs in USD per reference unit for turning alternatives.

	USD/reference unit
Wet machining total (without Titanium):	
Cutting insert production	9.876
Cooling lubricant production	0.035
Electricity in turning process	0.21
IC dry machining total (without Titanium):	
Cutting insert production	29.278
Cooling lubricant production	0.001
Electricity in turning process	0.168
IC wet machining total (without Titanium):	
Cutting insert production	2.788
Cooling lubricant production	0.036
Electricity in turning process	0.231

Table SI 8: CO_2-emissions in kg per USD input.

	CO_2-emissions per USD (PLCA)

Wet machining total (without Titanium): Cutting insert production Cooling lubricant production Electricity in turning process	 0.01 0.28 5.29
IC dry machining total (without Titanium): Cutting insert production Cooling lubricant production Electricity in turning process	 0.01 5.29
IC wet machining total (without Titanium): Cutting insert production Cooling lubricant production Electricity in turning process	 0.01 0.28 5.29

Overview of relevant sectors identified in Exiobase 2 for first order inputs necessary for IOLCA and HLCA of welding processes.

Wire is suggested to be part of **Other non-ferrous metal production**
inert gas: corgon (A), CO_2 (B) is suggested to be part of **Chemicals nec** electricity consumption is suggested to be part of Production of electricity **by coal**, **by gas, by nuclear, by hydro, by wind, by petroleum and other oil derivates, by biomass and waste, by solar photovoltaic, by solar thermal, by tide wave ocean, by Geothermal** and **Production of electricity nec**
welding flux powder is suggested to be part of **Other non-ferrous metal production**

Overview of relevant sectors identified in Exiobase 2 for first order inputs necessary for IOLCA and HLCA of turning processes.

Cutting insert production is suggested to be part of **Manufacture of machinery and equipment nec.**
Cooling lubricant production is suggested to be part of **Chemicals nec** Electricity in turning process is suggested to be part of Production of electricity **by coal**, **by gas, by nuclear, by hydro, by wind, by petroleum and other oil derivates, by biomass and waste, by solar photovoltaic, by solar thermal, by tide wave ocean, by Geothermal** and **Production of electricity nec**

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