THE CO$_2$PE!-INITIATIVE (COOPERATIVE EFFORT ON PROCESS EMISSIONS IN MANUFACTURING)

International Framework for Sustainable Production

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Abstract

Manufacturing processes are responsible for a substantial part of the environmental impact of products but are still poorly documented in terms of their environmental footprint. The lack of thorough analysis of manufacturing processes has as consequence that optimization opportunities are often not recognized and that improved machine tool design in terms of ecological footprint has only been targeted for a few common processes. At the same time, a trend can be observed towards more energy intensive, unconventional processing techniques. In order to address these shortcomings, a worldwide consortium of universities and research institutes launched the CO$_2$PE!–Initiative. This initiative has as objective to coordinate international efforts aiming to document and analyze the overall environmental impact for a wide range of available and emerging manufacturing processes with respect to direct and indirect emissions, and to provide guidelines to improve these processes. In addition to life cycle analysis, in depth process analysis also provides insight in achievable environmental impact reducing measures towards machine builders and eco-design recommendations for product developers. In this paper, the CO$_2$PE!-Initiative is described along with an overview of case studies to illustrate how the CO$_2$PE! methodology works.

Keywords

CO$_2$PE!, unit process, environmental impact, sustainable manufacturing

1. Introduction

Life Cycle Assessment (LCA) is one of the main tools for sustainability analysis, evaluating the environmental impact of a product or process along all of its life cycle phases, i.e. from cradle-to-grave or from cradle-to-cradle. However, its data-intensive character forms the major disadvantage of LCA. It is a well-known fact that performing a fully-fledged LCA study requires a time-consuming and data-intensive effort, while at the same time not all required data are readily available in Life Cycle Inventory (LCI) databases.

This lack of data is especially true for discrete manufacturing processes. In comparison with the intensive LCI data collection efforts on materials and chemical production processes, discrete manufacturing processes are still poorly documented in terms of their environmental footprint. Data in current LCI databases are often either lacking or based on very incomplete and sometimes even merely theoretic (under-)estimations.

On the other hand, the development of discrete manufacturing processes is heading towards more energy intensive, non-conventional manufacturing processes (Gutowski et al., 2006). These new manufacturing techniques, e.g. electro-chemical, laser and plasma-based processes, also generate emissions that have hardly been investigated from an environmental perspective. These undocumented and hard to control material flows are likely to imply significant potential human health as well as ecological hazards.

In order to overcome the lack of thorough environmental impact data of discrete manufacturing processes in LCI databases, the CO_2PE! (Cooperative Effort on Process Emissions in Manufacturing) – Initiative (CO_2PE!, 2010) has been launched. This initiative has the objective to coordinate international efforts aiming to document and analyze the overall environmental impact for a wide range of available and emerging manufacturing processes with respect to their direct and indirect emissions. Prospective environmental performance improvements of the manufacturing processes will also be identified. The initiative is officially recognized by the International Academy for Production Engineering (CIRP) as part of the Collaborative Working Group on Energy and Resource Efficiency and Effectiveness (EREE, 2009) and the Intelligent Manufacturing System (IMS) as Manufacturing Technology Platform Theme (IMS, 2008). A large number of research institutes and associated industrial partners in different continents have already joined the CO_2PE! - Initiative and share the required expertise and facilities among each other. The coordinated effort will contribute to LCI data as required for a systematic LCA study, covering the production stage of an individual product. Another important target of the initiative is to derive ecodesign guidelines for machine tool builders and best practice reference specifications for future generations of machine tools.

The main objective of this paper is to describe the CO_2PE! - Initiative. The corresponding framework and methodology of the initiative are explained and discussed as to how they could assist involved partners in collecting, documenting and contributing data. Case studies are provided in order to illustrate how the proposed framework and methodology work.

2. CO_2PE! Framework

The activities of the CO_2PE! - Initiative can be subdivided into four categories (CO_2PE!, 2010). Firstly a joint methodology for data collection and documentation is conceived (Activity 1). Intensive interaction and cooperation between experts in the domains of manufacturing processes research, LCA methodology development and product design techniques are required to construct a generic and consistent methodology suitable for systematic data collection and analysis for a wide range of manufacturing processes.

Secondly the coordinated data collection effort comprises the core of the initiative (Activity 2). Based on a systematic taxonomy of manufacturing (related) unit processes (DIN 8580, 2003), a worldwide data collection effort is being coordinated. Exchange of researchers and equipment as well as sharing of experience and comparison of data is characterizing this activity. A centralized overview and coordinating effort allows avoiding undesirable redundancy in data collection efforts while facilitating direct communication between parties with overlapping interests and expertise needs. The coordinative effort is based on the matrix scheme shown in Figure 1.

Thirdly the CO_2PE! - Initiative partners perform data sharing in function of systematic analysis (Activity 3). Several research institutes have committed to allocate master and PhD students to the analysis of the data that will be obtained as result of the efforts coordinated in Activity 2. Using the methodology emerging from Activity 1, parametric models need to be developed by linking workpiece features, which can be derived from part specifications, to emission estimates for the selected manufacturing processes. In order to assure a statistically sound outcome of these analysis efforts, systematic access will be provided to the data collection results of all CO_2PE! partners focusing on a specific manufacturing process. On operational level, parallel working sessions, dedicated to the different process communities, will be held as part of the workshops that will be organized, scheduled as part of or immediately before or after relevant international conferences.

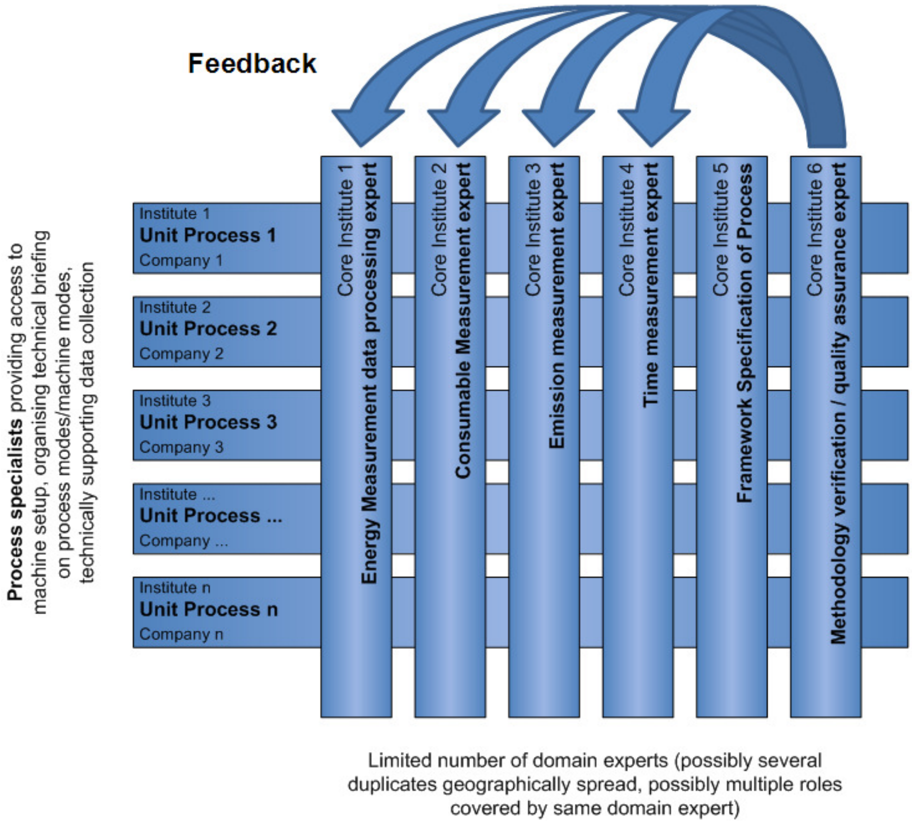

Figure 1: Organization of the CO_2PE! Initiative (CO_2PE!, 2010)

Finally, an extensive documentation of data collected and analysis results obtained for the different manufacturing processes is an explicit target (Activity 4). These results will be made available through easily accessible channels (such as on-line databases supported by different partners in the initiative) and on a cost sharing basis ("shareware" or whenever feasible, "freeware") and provided to LCA tool developers for inclusion in unit process LCI databases. Obtained results will be announced to a broad public through dedicated symposia and workshops at conferences. Best practice recommendations will be derived from the analysis results. While device specific advice will be provided to the involved machine tool builders, as direct feedback and return of investment for the time and effort spent in the data collection phase, generic recommendations will be formulated towards worldwide machine tool developers. The manufacturing process taxonomy tree will be screened for appropriate recommendation levels that can lead to the generation of "a best available technology reference" as a first step in the direction of eco-labeling of machine tools. The overall activities of CO_2PE! - Initiative are depicted in Figure 2.

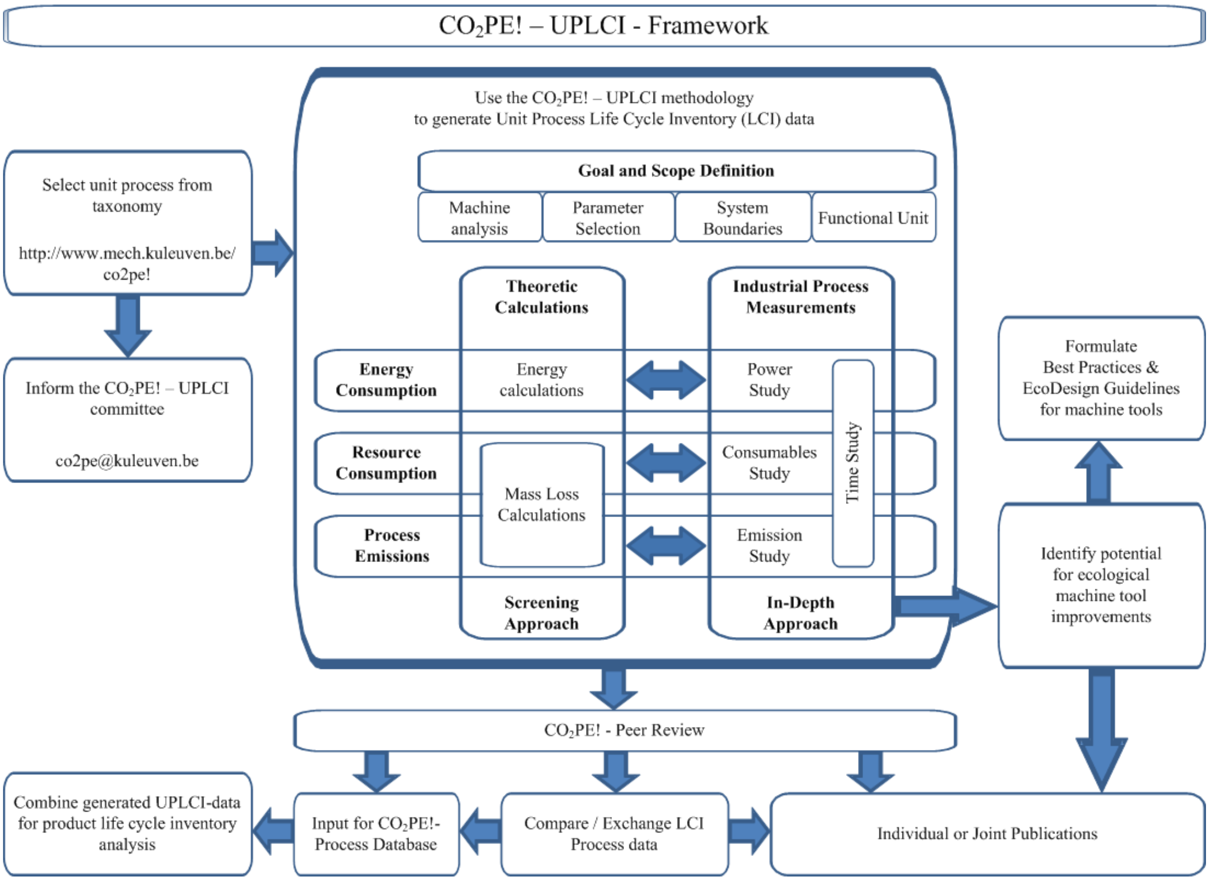

Figure 2: Overview of the CO$_2$PE! – Initiative framework and methodology (Kellens et al., 2010a)

3. CO2PE! Methodology

As described in the previous paragraph and shown in Figure 2, the CO$_2$PE! methodology plays a major role for ensuring systematic and standardized inventory analysis of manufacturing unit processes. It concerns an LCA-oriented methodology suited for the compilation of unit process life cycle inventories (UPLCI). The methodology will be briefly introduced in this section. A more detailed description of the methodology can be found in Kellens et al. (2010a).

3.1 Goal and Scope Definition

First the goal and scope of the study should be clearly defined and must be consistent with the intended unit process. The most important aspects to be considered are the system boundaries and the functional unit of the intended process. Furthermore, both the most influential process parameters and the machine tool architecture are investigated and all sub-processes and production modes are identified and located.

The system boundary determines which unit process shall be the subject of the study and which sub-processes (level of detail) for the selected unit process will be investigated. Besides studies at machine tool level, more extensive studies on sub-process level can be performed, e.g. in support of eco-design guidelines and machine tool design optimization in a later stage. The functional unit, which must be clearly defined (quantitatively as well as qualitatively) and measurable, serves to define a reference flow to which all other input and output flows of the process quantitatively relate. A functional unit must provide a unique basis for comparison between different process alternatives, e.g. the amount of removed material in the case of machining process.

The parameters or conditions of the input that govern LCI characteristics as well as the generated characteristics in the output product are listed based on available process experience and literature. Some parameters are strongly correlated to the created environmental impact while others are of minor importance, but may be vital in a product quality sense. Therefore, the list of parameters is ranked, in an approximate way, from largest to least effect.

Finally, the machine tool architecture will be investigated before the actual inventory analysis of the machine tool takes place. The typical use scenarios of the machine tool are considered. The energy and resource consuming units as well as the emission generating sub-processes of the machine tool under investigation are identified together with their function and location.

3.2 Inventory

The process inventory comprises two approaches with different levels of detail: the screening approach and the in-depth approach. The screening approach relies on representative general data and theoretical calculations for energy use, material loss, and identification of variables for improvement. In this approach, the total energy is determined based on a functional unit output and typically consists of two parts: the direct, incremental energy and the fixed energy from auxiliary systems. The mass loss calculations include contributions from basic material loss (removed material), auxiliary chemicals, unit process malfunctioning, etc.

The in-depth approach is based on industrial process measurements and is subdivided into four modules, including a time study, power consumption study, consumables study and emissions study, in which all relevant process inputs and outputs are measured and analyzed in detail.

During the first step of the in-depth approach, a time study is performed in order to identify the different production modes of a machine tool and their respective shares in the covered time span. The time study is based on observations of different production environments (companies) for multiple full shifts, including start-up and shutdown phases. The identified modes start from the machine tool start-up, over the use phase to finally switching off the machine. Six main production modes are pre-identified: start-up, full power, partial power, standby, shutdown, off and other mode.

The energy consumption of a process is then determined by performing the power consumption study. Since energy use is determined by the supplied power multiplied by the duration of an operation, the consumed electrical power should be measured for all identified production modes. After the various production modes of a specific process are identified during the time-study, these are subsequently scrutinized by measuring the power consumption of the complete machine tool as well as of all relevant energy consuming units active in each production mode.

Parallel to the time and power measurements, the consumables and emissions in each production mode are observed and documented. Examples of consumables are: compressed air, lubricants, process gasses and process filters. Gaseous, liquid and solid emissions (e.g. unrecyclable waste material), as well as waste heat, must be taken into account in emission measurements.

Both the screening and in-depth approaches have already provided useful results in some initial case studies conducted at Wichita State University (UPLCI, 2010) and Katholieke Universiteit Leuven (Devoldere et al., 2007, Duflou et al., 2010), respectively. The next section describes some examples.

4. Case studies

An overview of two case studies is given to illustrate the CO_2PE! methodology. Drilling and laser cutting processes are selected as case studies for the screening and in-depth approach respectively. A more detailed discussion of both case studies can be found in Kellens et al. (2010b)

4.1 Example of the screening approach: The drilling process

The main objective of this study is to analyze the energy and resource consumption in a specified drilling process (Kalla et al., 2010). The work piece is a 100x100x50 mm grey cast iron block, on which 4 symmetrical 19 mm diameter holes are drilled along its thickness. The drilling process is performed on a 4-axis CNC machine in a high production mode. The drilling process is done with one set of cutting parameters.

The energy calculation is conducted by summing up the product of required power and time for different modes, namely basic (standby), idle (partial) and drilling mode (see Equation 1). The calculated values for each variable for one and four holes are listed in Table 1.

$$E_{total} = P_{basic} \cdot (t_{basic}) + P_{idle} \cdot (t_{idle}) + P_{drilling} \cdot (t_{drilling}) \qquad (1)$$

Table 1: Time, power and energy required for the drilling process

	t_{basic} (s)	t_{idle} (s)	$t_{drilling}$ (s)	P_{basic} (kW)	P_{idle} (kW)	$P_{drilling}$ (kW)	E_{total} (kJ)
1 hole	77	33,3	27	7,5	10	0,69	926,5
4 holes	177	133	108	7,5	10	0,69	2733

It should be noted from Table 1 that the handling time and loading/unloading are already taken into account in idle time and basic time, respectively. The spindle, coolant and axis power are included in the idle power, while the basic power of the machine tool is assumed as 25% of the machine maximum in manufacturer specifications. Details of calculation and formulas are available in Kalla et al. (2010).

As for the mass loss calculations, it is performed by calculating the volume of material removed for a hole ($V_{removal}$ = 14.169 mm^3) and multiplying it with the material density to obtain the chip mass (m_s = 0.10 kg/hole). Another type of mass loss which needs to be considered in the calculations is the cutting fluid waste. By incorporating data from Clarens et al. (2008), it is found that the mass loss of the cutting fluid is 1.1 g/hole. A more detailed cutting fluid waste calculation can be found in Kalla et al. (2010).

4.2 Example of the in-depth approach: The laser cutting process

The in-depth approach case study is performed on a high power (5kW) conventional CO_2 laser cutting machine tool for sheet metal cutting operations (Duflou et al., 2010). The laser cutting is employed to cut the same contours on a 1 mm thick steel sheet with three different laser output powers (5 kW, 2.5 kW and 1 kW).

4.2.1 Time study

In order to identify the different operations on a laser cutting machine, a time study has been performed. Six hours of cutting operation for three distinct orders were filmed and subsequently analyzed. As listed in Table 2, six different operations could be distinguished. The actual cutting process is responsible for 85% of the total time. The remaining time is divided over table changing, program loading, changing laser head and other short activities.

Table 2: Production modes and relative time distribution of laser cutting operations

	Production Mode	% of total time
A	The laser is cutting sheets of metal or moving from one place on the sheet to another to start a new contour	84.9%
B	The machine changes its tables from the casing to the loading and unloading area	6.4%
C	The machine is standing still because the laser program is loaded or adapted	0.8%
D	The machine stands still because the laser head is changed (lens exchange)	0.4%
E	The machine stands still because a workpiece is taken out to check	4.5%
F	The machine stands still, without an obvious reason	3.8%

4.2.2 Power study

Figure 3 shows an overview of all possible production modes of the CO_2 laser cutting machine, with the total power consumption indicated by the blue line. Mode O1, O2 and O3 show three different power levels of a switched off machine. Mode O1 starts from no power requirement and gradually switches in small machine units (MU). The low power level of O1 is never reached in a standard manufacturing context since MU in the electrical cabinet are turned off manually. Mode O2 (4.5 kW) and mode O3 (1.3 kW) represent the lowest reachable energy levels when the laser machine is switched off in winter mode and in summer mode respectively. In winter mode O2, a 3 kW pump inside the chiller circulates water of the cooling circuit. The dissipated heat of the pump is used to warm the cooling water. If the water nevertheless reaches a temperature below 20℃, a 9 kW heating system will be activated. During the measurements in June, this stadium was never reached since the ambient temperature was always above 20℃.

When starting up (SU) the machine, the laser source runs through an initial cycle of about 12 minutes. During this calibration period, the total power increases from 4.5 kW (O2) to 59 kW. The laser source is now ready for cutting operations and total power stabilizes at approximately 27 kW, hereafter referred to as the standby (SB) mode. This power can be lowered to 10 kW by switching to the 'high voltage off' mode. This action un-excites the laser source and therefore causes less dissipated heat and cooling power.

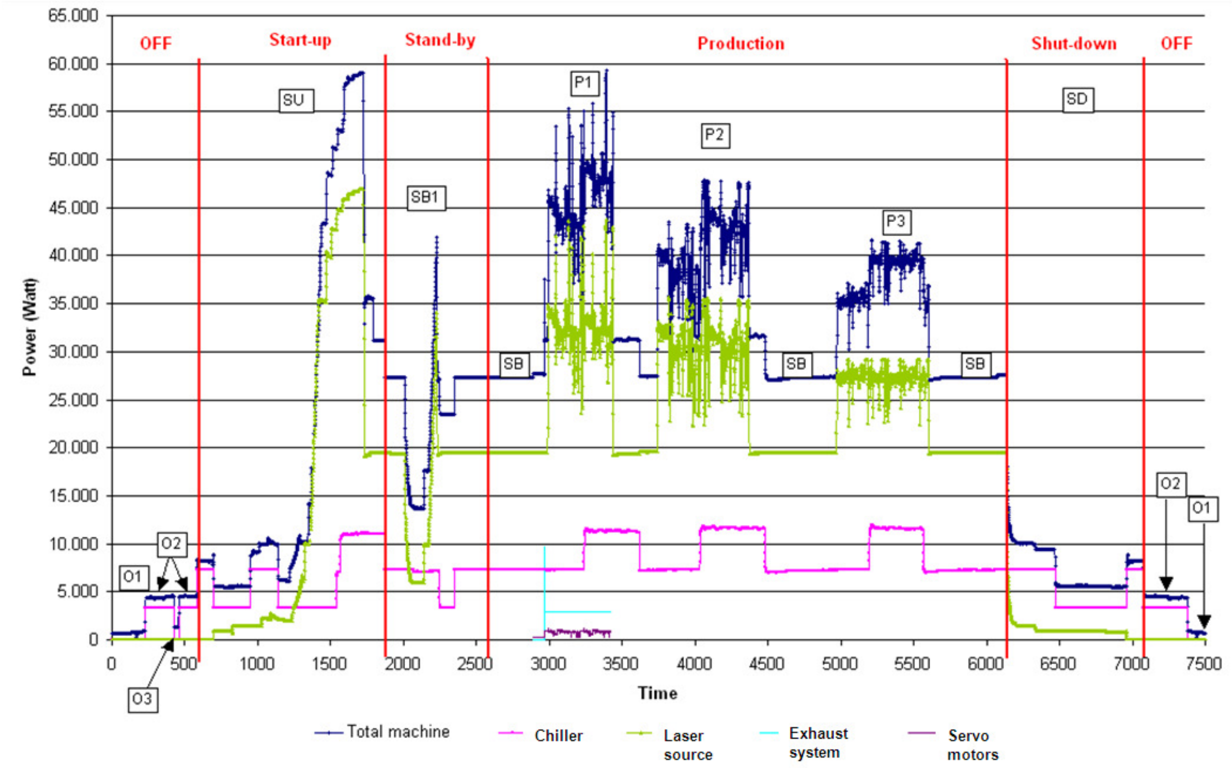

Figure 3: Overview of the power consumption in different production modes of a 5 kW CO_2 laser cutting machine (Duflou et al., 2010)

P1, P2 and P3 in Figure 3 show three production runs, each time cutting out the same contours in a 1 mm thick steel sheet with respectively 5 kW, 2.5 kW and 1 kW laser output power. At these moments, the total power displays large fluctuations linked to the fluctuations of the laser source power. At the end of production, first the laser source is shut down, resulting in a total power decrease from 27.3 kW to 9.4 kW. A few minutes later, also the cooling unit's power drops. Consequently, the total power declines to 4.5 kW, the power level when the machine is turned off in winter mode.

Figure 3 also depicts the power consumption of individual machine unit, namely the laser source (green line), chiller (purple line), servo motors (dark purple line) and exhaustor (light blue). It can be seen that the laser source and chiller unit are the major power consumers. During production runs, the demanded laser source power fluctuates largely. The reason is that the demanded output power is different for different operations, i.e. piercing the sheet, cutting the sheet or moving between contours. As for the chiller, its power consumption jumps one step higher each time an extra compressor is activated (Figure 3).

4.2.3 Energy study

Combining the data from the power study and the time study allows estimating the share of each mode in the total energy consumption, as depicted in Figure 4. For laser cutting processes, it is clear that the productive mode (from a process perspective), and the laser source unit (from a machine tool perspective) are the major contributors to the electricity consumption.

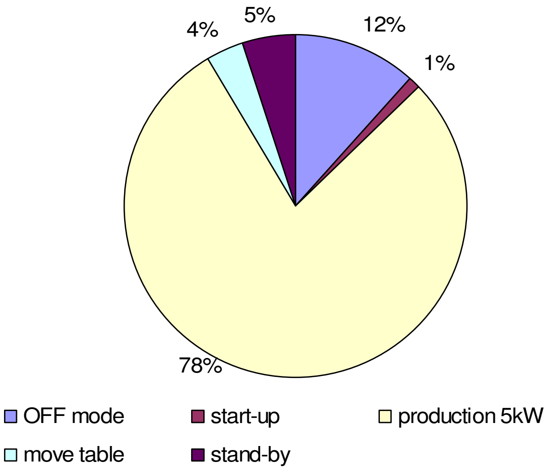

Figure 4: Relative energy consumption for each mode of a 5 kW CO_2 laser cutting machine (Duflou et al., 2010)

4.2.4 Consumables and emissions study

In this study the consumable study is focused on the cutting gas. The cutting gas is nitrogen (N_2) which is used as assist gas during the cutting process. The cutting gas flow rate is varying according to the material and thickness of the plate. For steel sheet, the flow rate is ranging from 16 m^3/s for a 1 mm sheet up to 50 m^3/s for a 6 mm plate (Serruys, 2002).

Emission measurements from Laser Zentrum Hannover are considered for the emission study in the current in-depth approach of laser cutting (Laser Zentrum Hannover, 2010). There are three main emissions: aerosols (1.1 mg/s), nitrogen oxide (0.0023 mg/s) and nitrogen dioxide (0.0029 mg/s).

5. Conclusions

The CO_2PE! – Initiative aims to document and analyze the environmental impacts of a wide range of discrete manufacturing processes and to provide guidelines to reduce these impacts. The initiative tries to accomplish this goal by coordinating international efforts of worldwide universities and research institutes. The corresponding framework and methodology have been proposed in order to foster effective, systematic and standardized data collection, analysis and communication. Two representative case studies have been briefly described to illustrate the two different approaches of the CO2PE! – UPLCI effort.

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