Subtractive versus mass conserving metal shaping technologies: an environmental impact comparison

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Abstract

The scientific studies in the domain of environmental sustainability of metal processing technologies predominantly focus on conventional material removal processes, as milling and turning. Despite some exceptions, many other non-machining technologies, such as metal forming processes, are still not well documented in terms of their energy and resource efficiency. Moreover, to properly evaluate the environmental impact of a given process, a standing-alone approach is no longer sufficient. In order to offer a valuable contribution in the domain of metal shaping sustainability, the present paper proposes a thorough methodology entailing to compare, from the environmental point of view, two traditional technologies: a hot extrusion process (mass conserving approach) and a turning (subtractive) one. A Life Cycle Assessment (LCA) based approach is implemented to properly analyze the considered processes. An axy-symmetric aluminum component was selected to develop the analysis on. Besides the analysis of material flows occurring all along the life cycle of the component, the material use and the consumed electrical energy necessary for the tools manufacturing are measured to properly quantify the environmental impact of the production phases. The most relevant influencing factors within each technology are identified and quantified. Moreover, an analysis of the environmental performance of the two processes at the varying of the batch size is presented. The paper aims at–providing some general guidelines for the identification of the greenest technology as the main influencing factors change.

Keywords: Extrusion, Machining, Sustainable manufacturing, LCA, Environmental impact comparison

1. Introduction

It is by now well known that reducing CO_2 emissions is an urgent objective to pursue. Such statement is true at a global scale, and it is particularly true as the industrial sector is concerned. Many initiatives in the domain of energy and resource efficiency have already been launched at a worldwide scale. Nevertheless, world CO_2 emission rose by 2.7% over 2011. The industry plays a relevant role, and it accounts almost for the 40% of the total consumption (IEA, 2013). The indirect emissions, caused by the use of electricity, currently represent the 18% of the total amount. This scenario becomes dramatic if the appraisals from the International Energy Agency are considered: by 2035 the demand for electricity will increase by 70%. The scientific as well as the industrial world have gathered such challenge, starting to find out energy and resource efficient manufacturing strategies (Duflou et al., 2012).

When a component has to be produced, in most cases more than one manufacturing technology can be used. In the recent past, the technology to be implemented was selected mainly on the basis of cost, productivity, or technical indicators. Nowadays, such criteria are no longer sufficient, and the environmental impact has to be considered in the decision step. As long as the technological feasibility of a given process is guaranteed, processes minimizing resources and energy consumption have to be selected to manufacture a given part. The here proposed research aims at analyzing different production technologies, i.e. two different ways to shape metal components: a mass conserving (forming process) and a subtractive approach (machining process). Material plays a relevant role as the environmental impact of a product is concerned. Minimizing material use in production is, therefore, an important strategy to pursue for reducing the CO_2 footprint of a given component. Material scraps should be minimized even when benefits deriving from recycling are considered. The comparison of two technologies characterized by different amount and kind of materials could lead to interesting conclusions in the domain of CO_2 emission minimization. As a more general issue, the manufacturing world has to face concerns the finding of new technologies, and such futures technologies cannot leave sustainability concerns out. A systematic analysis and comparison of processes is an urgent research to develop. As a matter of fact, such kind of research can help in identifying the manufacturing strategy able to satisfy the new market and society requirements: high complexity, lightweight and "green" products.

1.1. Literature review

In order to select the proper technology, a full awareness about the environmental impact of all the existing technologies should be available. In this respect, the CO_2PE! initiative has the objective to coordinate international efforts aiming to document and analyze the overall environmental impact of a wide range of available and emerging manufacturing processes, and to provide guidelines to improve them. The growing interest in quantifying the CO_2 footprint of such processes led to the development of a methodology for the systematic analysis and improvement of manufacturing unit process life cycle inventory (UPLCI) (Kellens et al., 2012). Nevertheless, nowadays the reported studies on sustainability analysis of metal processing predominantly focus on conventional material removing processes, such as turning, milling, and grinding.

Some researchers focus on the measurement, quantification, and minimization of electric energy consumption. Devoldere et al. (2007) discussed about the potential for energy improvement, with particular attention to the fixed energy demand of machine tools, the importance of their architecture, and the production modes share. The research developed by Diaz et al. (2010) dealt with the effect of the material removal rate on electric energy consumption, whilst Kara et al. (2011) presented an empirical model to characterize the relationship between energy consumption and process variables for material removal processes. Avram and Xirouchakis (2011) offered an energy consumption reduction perspective by considering alternative machining strategies, with respect to various use-phase regimes of a machine tool system. Campatelli et al. (2013) proposed a response surface based approach to model the power consumption in a milling process performed on a modern CNC machine. Balogun et al. (2013) defined a mathematical model for predicting the direct electrical energy requirements in machining processes, taking into account the machine tools' architecture, the operational productive mode, and the sub-unit power consumption. A further energy consumption model for the milling process was presented by Li et al. (2013): an improved model, as a function of material removal rate and spindle speed, was tested and validated under various cutting parameters. An optimization approach was also proposed by Bhushan et al. (2013). In particular, the machining parameters were optimized by multi-response considerations, namely power consumption and tool life, during machining of 7075 Al alloy with 15 wt.% SiC particle composites. Yan et al. (2013) developed a multi-objective optimization method for cutting parameters in milling, to evaluate the trade-offs between sustainability, production rate and cutting quality.

Others researches in the domain of machining process sustainability focus on the effect of cutting fluids. A critical review on the lubrication techniques in machining was presented by Lawal et. al (2013), while Lawal et al. (2014) compared the cutting performance of vegetable cutting fluids and mineral oil-in-water emulsion when turning an AISI 4340 steel. Davoodi et al. (2014) analyzed the effect of cutting speed and undeformed chip thickness on cutting and feed force components, and the tool tip temperatures were experimentally investigated to remove the cutting fluid. Sharma et al.

(2014) investigated the effect of dry and near-dry machining on an AISI D2 steel, by using a vegetable oil.

Other researchers focus on a global approach aimed at studying all the environmental influencing factors of machining processes. Gutowski et al. (2006; 2009) presented an environmental analysis carried out at a system level. In particular, a qualitative investigation was made, concerning the impact of the material removal process itself as well as the impacts related to material production, cutting fluid preparation, tool and machine tool construction. Gutowski et al. (2004) proposed a model able to calculate the electricity requirements for a manufacturing process, as a function of the process type and of the rate of the material processing. It is worth pointing out that, in this approach, process parameters such as processing rate, workpiece hardness and specific cutting mechanics can be considered in the model. Narita et al. (2006) proposed a theoretical model able to evaluate the environmental burden of a machining operation, by taking into account several factors: electric energy consumption, cutting tool status, coolant quantity, lubricant oil quantity and metal chip quantity. An interesting research was also developed by Rajemi et al. (2010): the aim of their work was to create a new model and a new methodology for optimizing the energy footprint of a machined product. In this research the environmental impact of cutting tool was included in the sustainability analysis. A recent example of global machining processes modeling can be found in the work of Kuram et al. (2013): the effects of cutting fluid types were investigated as a function of three milling factors (cutting speed, depth of cut, and feed rate) on process responses (specific energy, tool life, and surface roughness). Mono- and multi-objective optimization studies were conducted using the responses as objectives to optimize. A further innovative approach was developed by Díaz-Tena et al. (2014), in which the use of bacteria in machining was considered as a renewable natural source of tools. As far as grinding is concerned, an overview on the sustainability of the processes (analyzing the environmental, social, and economic point of view) was recently published by Aurich et al. (2013). Winter et al. (2013) presented a Pareto-based approach for characterizing the grinding processes in terms of their technological, economic and environmental impact; a new methodology to determine optimal process parameters to improve eco-efficiency was presented as well.

In literature some exception on environmental analysis of non-machining technologies can be found. In particular, Kellens (2013) analyzed, by using a systematic approach, the environmental performance of laser cutting, Selective Laser Sintering (SLS) and Electric Discharge Machining (EDM). Recently, some research groups published environmental analyses on additive manufacturing. Kellens et al. (2014) provided accurate estimations of the environmental footprint of SLS processes based on two design features. Their research concerned energy and resource consumption as well as process emissions. Le Bouhir et al. (2013) presented a new methodology in which all the resource flows (material, fluids, electricity) were considered in the environmental impact assessment. Baumers et al. (2013) discussed the implementation of a tool for the estimation of process energy flows and costs occurring in the direct metal laser sintering.

In contrast to the conventional machining processes (e.g. milling, turning, etc.), metal forming processes are still less documented in terms of their energy demand (Ingarao et al., 2011). In particular, only a few studies related to the environmental impact of sheet metal forming processes can be found in literature. The most relevant contributions concern air bending (Santos et al., 2011) and incremental forming (Ingarao et al., 2014; Dittrich et al., 2012). Recently, a paper reporting a structured overview of the available studies on the energy demand of sheet metal forming processes was provided by Kellens et al. (2014). The main conclusion of the research was that, with the exception of air bending and single point incremental forming (SPIF) processes, sheet metal forming processes are rarely studied. As a consequence, substantial space for improvement in data collection can still be expected for this process category.

In order to properly label and sort the manufacturing routes in terms of sustainability features, besides standing-alone analysis, comparative approaches could definitely help in quantifying and analyzing electric energy as well as resources flows (material and consumables) of different production strategies. Unfortunately, only a few studies have already been performed by using comparative approaches. Serres et al. (2011) compared an innovative additive laser technology (CLAD) with a conventional machining process by applying an LCA approach, and taking into account both material and energy consumptions. Morrow et al. (2007) investigated three case studies to reveal the extent to which DMD-based manufacturing of moulds and dies can achieve reduced environmental emissions and energy consumption (relative to conventional manufacturing pathways). Other researchers compared innovative laser assisted processes with conventional ones from an environmental point of view. Zhao et al. (2010) evaluated the environmental performance of laser assisted processes with traditional methods. Dittrich et al. (2012) performed an exergy comparison of single and double side incremental forming, conventional forming (plastic and cast iron die set), and hydroforming processes.

1.2. Aim of the paper

From the literature review it is possible to notice that, in the last few years a strong effort aimed at understanding and modeling the environmental impact of the production processes was made by scientists. Some processes, like traditional machining, have already been widely analyzed, and some models able to link the environmental performance to the fundamental process parameters were proposed. On the contrary, two relevant knowledge gaps can be spotted:

- the metal forming processes (in particular bulk forming processes) are still not well documented in terms of their environmental impact;
- there is a lack of systematic and comparative studies on energy and material flows enabling the identification of environmental-friendly manufacturing design strategies.

The paper presents a starting attempt to tackle the knowledge gap emerged from the state of the art analysis. Furthermore, the study aims at providing a detailed methodology able to accurately analyze and compare metal shaping processes, and at describing and highlighting the most relevant environmental influencing factors for the considered processes.

The present research concerns an environmental comparison between a hot extrusion process (bulk forming process) and a machining process. In other words, two different production philosophies are compared from the environmental point of view. The two manufacturing approaches have not been yet compared in light of a sustainability perspective. A simple-shape aluminum component is considered to develop the analysis. In particular, a LCA based approach, able to take into account the environmental burden of different product life-cycle phases, is presented. The energy flows occurring during the material production, the manufacturing steps as well as the end-of-life phase are considered.

2. The analyzed case study

In order to compare the two technologies, a product obtainable with both the approaches was identified. A simple axy-symmetric shape was considered, and a diameter reduction process was selected. The sketch of the component, together with the manufactured specimens, are shown in Figure 1. As far as the material is concerned, the high strength AA-7075 T6 alloy was chosen because of its high industrial applicability, especially when weight reduction is an objective to pursue.

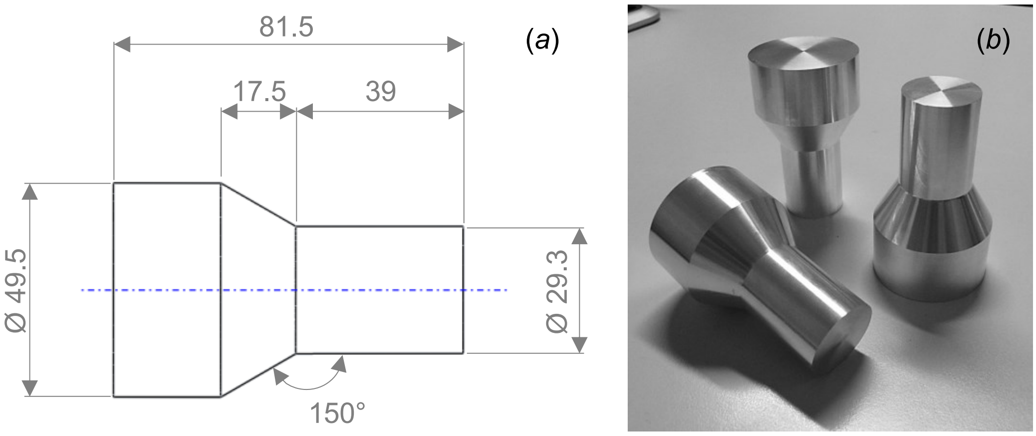


Figure 1. Investigated component: (*a*) sketch, (*b*) machined specimens.

2.1. The bulk forming process

A single hot extrusion step was applied to obtain the desired geometry. Actually, it is not a proper extrusion process, as the extrusion mechanics concern only a part of the billet. The equipment utilized to perform the forming process is shown in Figure 2. In order to keep the billet temperature within the range normally used to form this material, the billet was heated up by an electric furnace to 420°C, while the temperature of the die was kept constant to a temperature equal to 350°C. The die was heated up by using a band heater, whilst the ram speed was set equal to 1 mm/s: such value is a compromise between the necessity to reduce the forming time and the need to avoid an excessively localized temperature increment on the extruded surface (which could affect its quality). The parameters setting was designed by using a coupled thermo-mechanical model developed on Deform 2D. The temperature range as well as the friction conditions were set-up by following the guidelines provided by ASM international (2005). As far as the press is concerned, a four pillars electro-hydraulic Instron 1276 Machine with a load capability of 1000 kN was used. In order to properly measure the electric energy consumption along the whole working cycle, the press was equipped with an energy power-meter directly connected to the machine's electric cables and linked to a wireless data acquisition system.

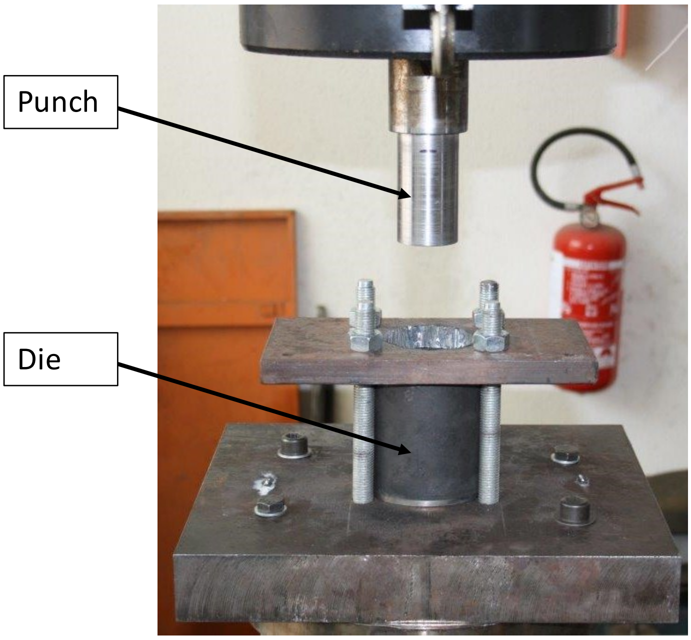


Figure 2. The equipment utilized for the extrusion process.

2.2. The machining process.

The turning tests were performed on a Cortini F120/25 CNC lathe (Figure 3). The spindle has a continuously variable rotational speed up to 7,000 rpm, whilst the maximum torque and the peak power are 35 Nm and 5.5 kW, respectively. The raw material was a pre-machined bar of AA-7075 T6 alloy, having the total length (*L* = 81.5 mm) and the outer diameter (*D* = 49.5 mm) equal to those of the finished component. The workpiece was clamped in the 3-points chuck of the machine tool, and the designed final geometry was obtained by means of two subsequent longitudinal external turning operations of roughing and finishing (Figure 4). CCGX 09 T3 08-AL H10 (tool holder: SCLCL 1212 F09-M) and coated DCMT 11 T3 08-KM (tool holder: SDJCL 1212-11) cutting inserts, provided by Sandvik Coromant, were applied for roughing and finishing operations, respectively. All the tests were executed by using fresh tools, under conventional flood cooling lubrication. Wet cutting was performed by a 5% emulsion of Roloil Biotem-AD soluble semi-synthetic oil in water. Different set of cutting conditions were considered in order to evaluate the effects on process performances. In particular, the cutting speed, feed, and depth of cut (in roughing) were progressively raised, as detailed in Table 1. A further increase of process parameters was not possible, due to the limited size/rigidity of the machine tool. The electrical power consumption was acquired by a Yokogawa WT130 power-meter clamped onto the electricity supply wires to the CNC lathe, and calibrated for a 3-phase, 3-load, 3-wire measurement. The electrical energy consumed by the machine tool for each produced component was calculated as the power integrated over the cycle time. The roughness of the machined surfaces was measured by means of a Hommelwerke Tester T1000, and the tool wear was observed by using a Leica MS5 optical stereo-microscope at 40× magnification.

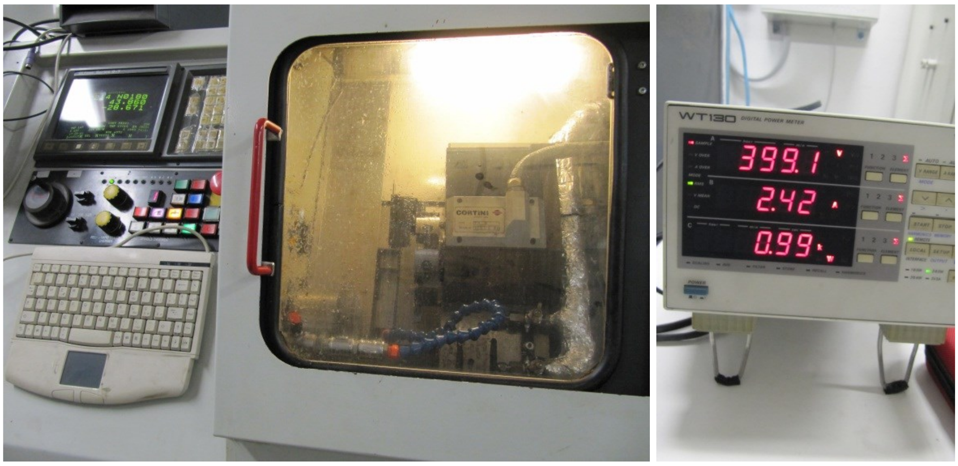


Figure 3. Experimental set-up for turning tests.

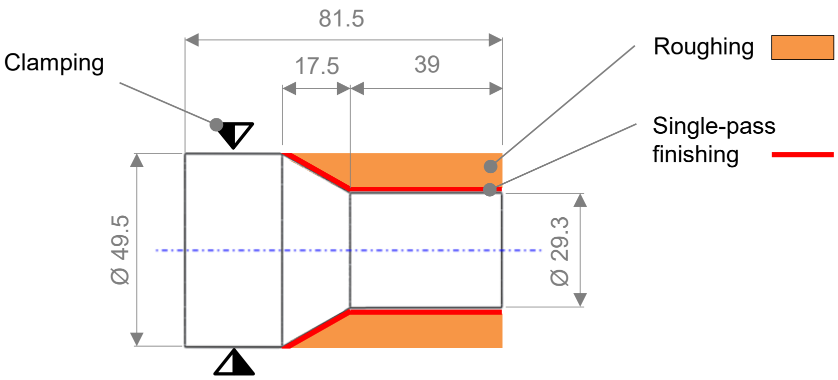


Figure 4. Sketch of the roughing and finishing operations.

Table 1. Process parameters applied when turning.

	Roughing			(Single-pass) finishing		
Test	v_c^* (m/min)	f (mm/rev)	a_p (mm)	v_c^* (m/min)	f (mm/rev)	$a_{p\ x,z}$ (mm)
1	100	0.15	0.75	150	0.10	0.25
2	150	0.225	1.08	225	0.15	0.25
3	200	0.30	1.50	300	0.20	0.25

Key: v_c = cutting speed; f = feed; a_p = depth of cut
* The cutting speed was set constant; the maximum spindle speed was limited to 4,000 rpm

3. The LCA based approach: system boundary and major assumptions.

The two manufacturing strategies strongly differ in terms of resource and energy usage. The forming process is basically a mass conserving approach, while machining proceeds by progressively removing material in the form of chips (therefore it consumes a higher amount of material). Moreover, the two strategies are characterized by different energy consumptions during the manufacturing step. As a matter of fact, these technologies use different machine tools (characterized by peculiar electric power absorptions), with strongly different working cycle-times. A LCA-based approach is, therefore, necessary in order to compare them. To properly quantify the environmental impact of a given product, all the main phases of its life have to be considered. The materials and the energy consumed in each phase have to be monitored, collected and quantified. Normally, the life cycle of a product is divided into 4 main phases: material production, product manufacturing, product use and product disposal (Ashby, 2012). The definition of the system boundaries is one of the first steps to take. The two technologies use different amounts of material to obtain the same final component. The material flow has to be followed all along its life by means of a cradle-to-grave approach. The material production impact as well as the end-of-life step have to be considered. Since the product use phase is common for both the technologies, it was not involved in the present study. In fact, assuming that the manufactured component complies with the same product specifications, the difference in environmental impact during the use phase can be neglected. A sketch of the considered LCA system boundaries is reported in Figure 5.

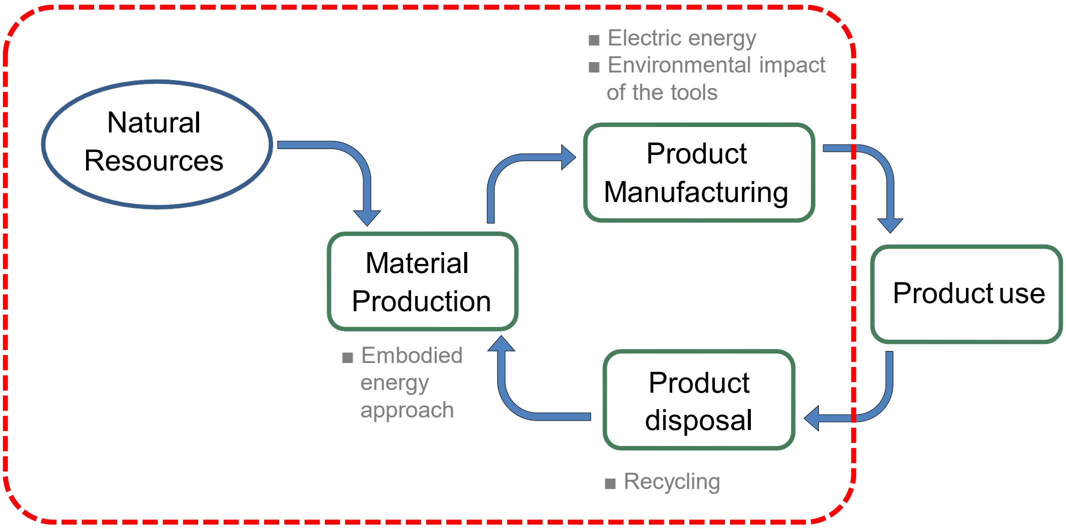


Figure 5. Sketch of the selected system boundaries.

Such boundaries can be labeled as a cradle-to-gate plus end-of-life approach. All the environmental impact due to the component manufacturing as well as the credit from recycling (end-of-life stage) were analyzed. In order to consider the benefit deriving from material recycling, the substitution method was applied (Ashby, 2012; Hammond et al., 2010). In this research, the concept of embodied energy was used. The energy per unit mass consumed in making a material from its ores and feedstock is defined as its embodied energy (Ashby 2012). For the analyses, the selected functional unit was the single component: the machining and the forming processes were compared in terms of environmental performance to obtain one part. During the manufacturing step, besides the electric energy consumption of the specific machine tool, the environmental impact related to the tools manufacturing was included in the analysis. The energy and the CO_2 emissions were considered as the variables representing the environmental impact. In particular, in order to obtain the CO_2 emissions due to the electric energy consumption, the Carbon Emission Signature (CES) method proposed by Jeswiet and Kara (2008) was used. The method is based on the following equation:

$$CES\ [g\ of\ CO_2/kJ] = 1/\eta \times (112 \times C + 49 \times G + 66 \times O)$$

where C, G and O are the fractions of coal, gas and oil, respectively, burned to provide the energy to the grid. An overall energy conversion coefficient $\eta = 0.34$ accounts for the energy losses occurring at the various single steps of the production of electricity out of fossil fuels (Nava, 2009). Finally, the carbon emissions can be calculated by multiplying the energy consumed by the Carbon Emission Signature in any system where electrical energy is used from a power grid whose power generation mix is known. In this study, the fractions of coal, gas and oil characterizing the Italian grid were considered.

4. Life Cycle Inventory data collection.

In this section, the description of the LCI stage of the methodology is reported. All the energy and resource flows involved in the considered processes are specified. The influencing factors within each manufacturing approach are described, and the methodology for quantifying the related environmental impact is explained.

4.1. The bulk forming process.

To measure the electric power absorbed by the hydraulic press while forming the billet, a power-meter was used. The electric energy consumed during the forming step was obtained by multiplying the power level by the forming time. In order to deal with the energy consumption during the non-productive mode, a time study was performed with the aim to identify the different use modes of the press and their respective shares in the covered time span. Four main production modes were identified: (*i*) billet loading/unloading, (*ii*) punching moving upwards, (*iii*) forming, (*iv*) punching moving downwards. For each production mode, the related time and the power consumption were computed. As far as the power is concerned, the press, because of the hydraulic-based architecture, shows a nearly constant power level over all the production modes. In particular, the press absorbs a power equal to 31 kW all along the working cycle. The whole working cycle takes 63.5 seconds, and Figure 6 shows the time share related to each production mode (considering a constant power level absorption, the figure also represents the share of the electric energy consumption).

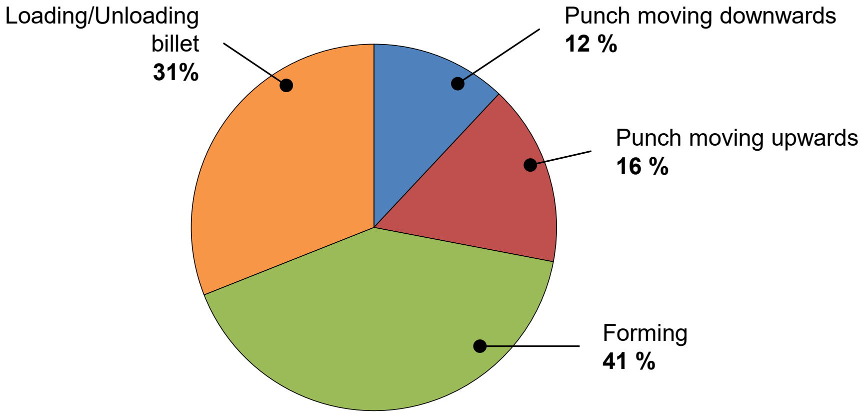


Figure 6. Time shares of different production modes when forming.

As the accounting for the environmental impact of the heating system is concerned, both data available in literature and experimental measures were used. In this research, the billets were heated up by a lab-scale electric furnace, however energy and CO_2 emissions data present in literature were preferred to better describe industrial practice (Kervik et al., 2006). Concerning the aluminum billet heating, even though some new and greener technologies were recently developed, the conventional gas furnace methods was considered in this research. It is worth pointing out that, the billet heating plays a relevant role in the environmental impact of forging. In fact, natural gas accounts for 70% of the whole metal forming sector's energy consumption. The majority of furnaces are heated by natural gas, and it is estimated that furnaces account for 85% of natural gas consumption in the forging sub-sector (Carbon Trust, 2011). In Table 2, the required energy and the CO_2 emissions to preheat the aluminum billet are reported (Kervik et al., 2006; Milford et al., 2011). For the die heating, a band heater was used: to account for the energy required to heat the die up, the power absorbed by the band was multiplied by the working cycle time (productive as well as non-productive time were both considered).

The environmental impact related to the die and punch production was included in the LCA analysis. To quantify the environmental impact related to the die manufacturing, both the impact due to the material use and to the electric energy necessary to obtain the desired die shape were included in the present study. For the punch, being a simple cylindrical-shape component, only the environmental impact related to the used material was taken into account. The material production phase has been included by considering the embodied energy of the AISI H13 used for both the die and the punch; furthermore the electric energy consumption related to the machining operation to obtain the final die shape was also evaluated. The embodied energy approach as well as the credit deriving from recycling were considered. Data concerning the H13 embodied energy and the processing energy were found on CES EduPack. In particular, both coarse and fine machining operations were expected to obtain the die. It is worth pointing out that, die is assumed to last for all the batch sizes considered in this study. The part obtained after the forming step is characterized by a small shape defect as shown in Figure 7, since a sort of curvature occurs at the bottom of the component. Such phenomenon is due to the different velocities characterizing the material flow while it is being extruded: the material in contact with the die walls is slowed down by the friction force actions and it is, therefore, slower than the inner material. In order to obtain the desired component, a subsequent finishing operation to eliminate the curvature has to be envisaged in the whole working cycle. A facing process developed on a lathe was considered and the related electric energy consumption was included in the LCA analysis. The finishing operation makes the forming process not a pure mass conserving one, in fact the 2% of the material is removed by the final machining operation. The extra amount of material has to be accounted in designing the processes. In other words, the extra material as well as the extra stroke have to be evaluated to design the process. In the present study, the process was properly planned by means of numerical simulations, which were used to identify the minimum extra amount of material. Figure 7 shows the output of the numerical simulation: the shape defect as well as the material to be removed are noticeable. It is worth pointing out that, the post-forming finishing operations were not considered in terms of electrical energy consumption. More in detail, for the present case study, the oxidation is not an issue. This can be explained because, even if the material is heated up before the forming phase, the process is usually carried out without lubricant and, therefore, sticking conditions can be observed between the external part of the billet and the die. The formation of this thin layer is really important for preventing the direct contact between aluminum and air during extrusion. Moreover, once the part exits from the die, it is readily cooled down and, consequently, no oxidation is usually observed on the extruded profiles.

For the present case study, the post-forming finishing operation would be still necessary for removing the curvature defect (Figure 7). Such operation, which is developed at the lathe, has however a negligible environmental impact when the other influencing factors are considered (the electric energy values differ by two orders of magnitude). Table 2 shows the most relevant inventory data for the AA-7075 workpiece material, whilst Table 3 reports the inventory data for the H13 tool material.

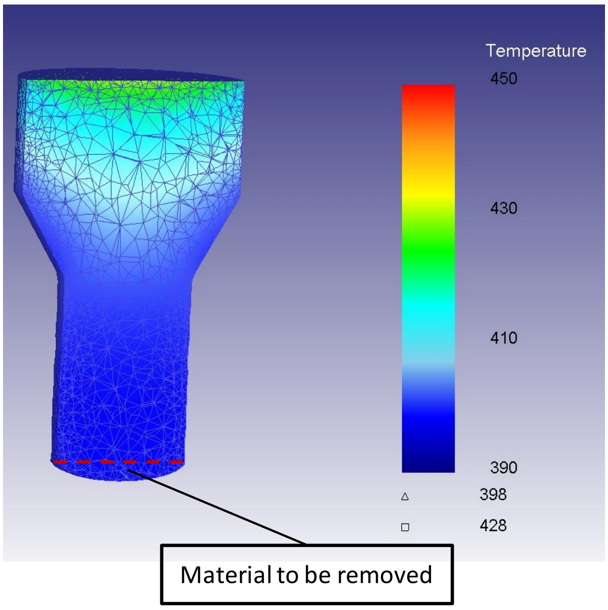


Figure 7. Numerical simulation output for the extrusion process.

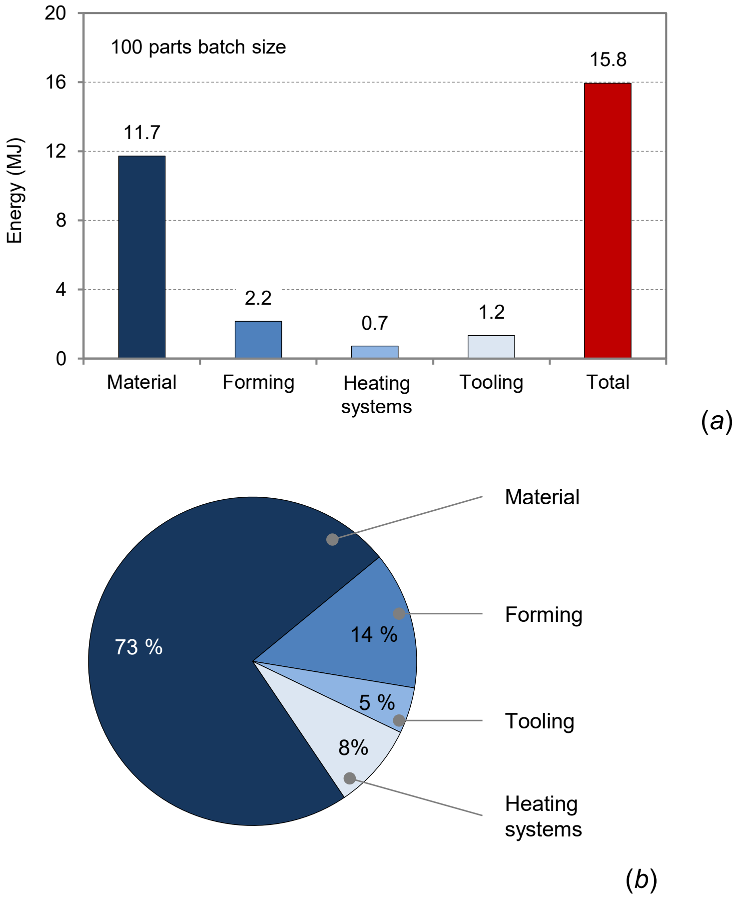
Table 2. Inventory data related to aluminum AA-7075.

Material	AA-7075
Amount of involved materials [kg]	0.27
Embodied Energy Primary Production [MJ/kg]	202
CO_2 footprint Primary Production [kg/kg]	12.7
Embodied Energy Recycling [MJ/kg]	34.3
CO_2 footprint Recycling [kg/kg]	2.7
Recycling ratio (Mayyas et al., 2012; Behrens et al., 2014; Paraskevas et al., 2012)	95%
Heating CFF Energy footprint[MJ/kg] (Kervik et al., 2006; Milford et al., 2011)	5.8
Heating CFF CO2 footprint (Kervik et al. 2006,Milford et al 2011) kg/kg	0.3

Table 3. Inventory data related to steel AISI H13.

Material	H13
Involved materials for Die production [kg]	6.43
Involved materials for Punch production[kg]	0.61
Embodied Energy Primary Production [MJ/kg]	71.7
CO_2 footprint Primary Production [kg/kg]	4.8
Embodied Energy Recycling [MJ/kg]	15.6
CO_2 footprint Recycling [kg/kg]	1.23
Recycling ratio (Mayyes at al., 2010; Hammond et al., 2010)	95%

The details of the energy consumption for the production of a part belonging to a batch size equal to 100 are reported in Figure 8. As it can be noticed, the energy consumption due to the material production is considerable, even if the energy credit deriving from recycling is fully considered. In particular, the energy consumption due to the raw material usage accounts for the 73% of the total energy amount. The electric energy consumed by the press all along the working cycle accounts for the 14% of the total, while a less relevant role is played by the heating systems and the tooling (accounting for a share equal to 5% and 8%, respectively). The same trend can be noticed by observing the CO_2 emissions caused by the different activities, as highlighted in Figure 8c.



(*a*)

(*b*)

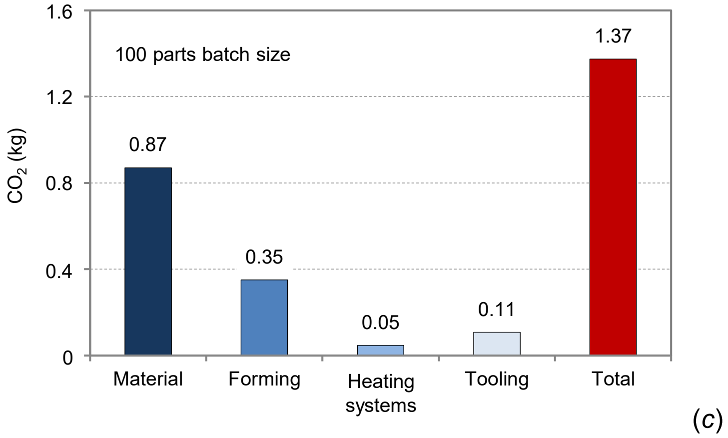
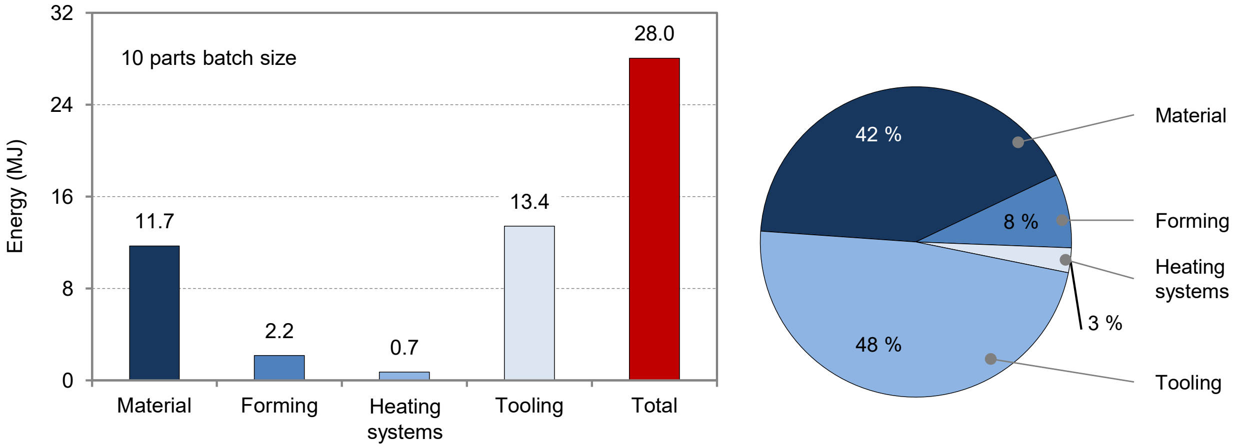


Figure8. Energy consumption (*a*), energy shares (*b*), and CO_2 emissions (*c*) for manufacturing one component belonging to a 100 parts batch size.

Among the environmental influencing factors, the contribution related to die and punch manufacturing is the only variable as a function of the batch size. In fact, the quantified environmental impact (energy and CO_2 emissions) has to be divided by the number of parts to manufacture. As a consequence, at the decreasing of the batch size, the environmental impact of the tools manufacturing assigned to each part increases. Such consideration leads to the conclusion that, the environmental impact of the single part manufacturing increases at the decreasing of the batch size. Figure 9 shows the energy consumption and the breakdown analysis of the energy shares for a scenario characterized by a batch size of 10 parts. As it can be observed, the impact of the tooling is now relevant. The energy contribution related to tool manufacturing increases of an order of magnitude (with respect to the results in Figure 8), and it accounts for the 48% of the total energy consumption. Even though the other energy components are unvaried, the total energy consumption for the production of a single part noticeably increases, up to 28 MJ.



(*a*) (*b*)

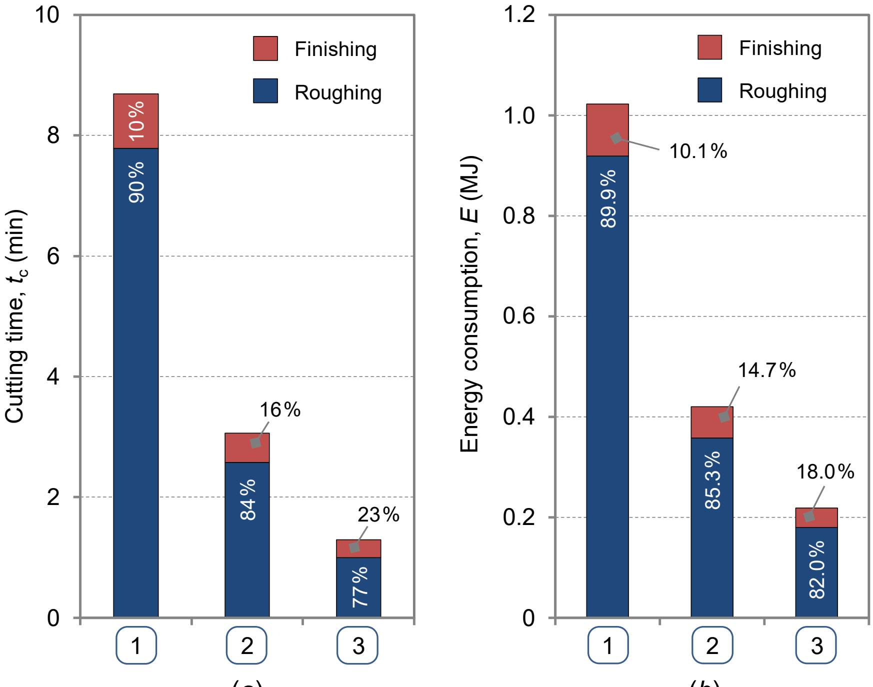
Figure 9. Energy consumption (*a*) and energy shares (*b*) for manufacturing one component belonging to a 10 parts batch size.

The analysis of these outcomes leads to some first assessments:

- the material consumption plays a relevant role in terms of the environmental impact, even if the credits from the recycling are considered;
- the impact of the material is noticeable also by analyzing the role played by the tooling, especially when small batch sizes are considered. In fact, the tooling is dominated by the consumption due to the H13 steel usage;
- In the domain of process sustainability analysis, the impact of tooling as a function of the batch size is a key issue to be studied.

4.2 The machining processes

When turning, the 41.2 % of the total mass of the workpiece is processed into chips. With respect to the chosen machining strategy, the 91.5 % of the scrap material is removed by roughing, and only the 8.5 % by the finishing operation which allows reaching the designed geometry of the part. As a consequence, this affects the results in terms of time and energy consumption. As shown in Figure 10, the greater amount of consumed energy and cycle time are attributable to the roughing phase, regardless of the test conditions. Moreover, when increasing the process parameters within the selected range, from Test 1 to Test 3 (with respect to Table 1), the cutting time is shortened from 8.7 to 1.3 minutes, and the energy consumption is reduced to about one fifth. There is a significant energy requirement to start-up and maintain the machine tool in a ready position. In addition, the power demand of the features required to support the process (by performing all the functions including work handling, lubrication, tool changing, etc.) dominates the power strictly related to the material removal (Rajemi et al., 2010, Gutowski et al., 2006). As shown in Figure 11, the adoption of the most demanding process parameters implies that, the portion of energy consumption due to the cutting process becomes in percentage greater, both for roughing and finishing, although the highest consumption is related to non-machining operations. Therefore, the strategy to lower the energy consumption should be the increase of the production rate, wherein the machining contribution is higher.



(*a*) (*b*)

Figure 10. Cutting time (*a*) and energy consumption (*b*) when turning. Cutting conditions 1-3 refer to Table 1.

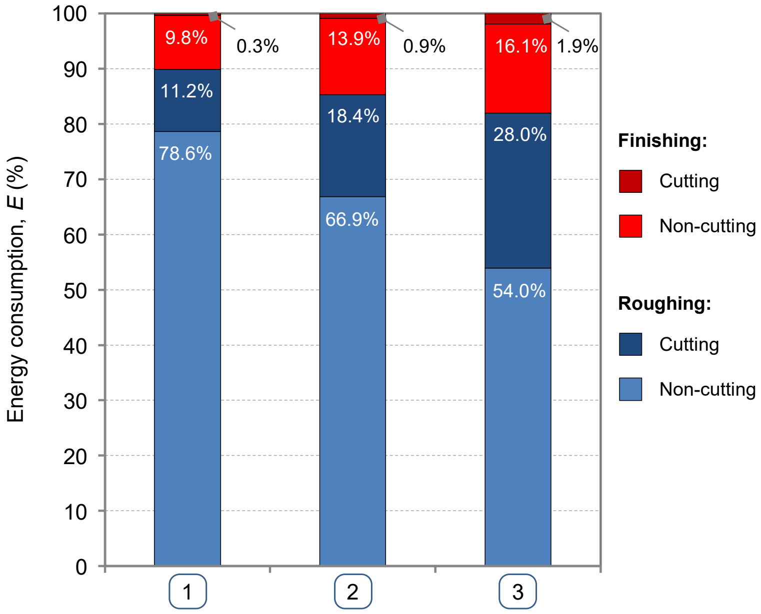


Figure 11. Influence of cutting and non-machining operations on energy consumption. Cutting conditions 1-3 refer to Table 1.

Within the selected range of process parameters (Table 1), the outcomes achieved in terms of surface quality/integrity and tool wear were used to define the optimum cutting conditions for the designed part. Figure 12 reports the surface roughness results under different finishing conditions. The histograms plots the average values of the arithmetic mean roughness R_a and of the maximum roughness profile height R_t, both calculated considering 20 measurements randomly acquired on each produced part. An increase of the roughness indices is detected when increasing the process parameters, and particularly when switching from Test 2 to Test 3. This evidence is also confirmed by the observation of machined surfaces by means of the optical stereo-microscope (Figure 12). Moreover, worn tools generate more deformations, together with poor finish, surface hardening and residual stresses. The replacement of worn tools with fresh ones entails an impact on the energy footprint of the cutting process. In some cases, such contribution could be neglected in comparison to all the other factors affecting the process, since a single cutting insert can be used to machine and produce a large number of components prior to its substitution. Figure 13 shows pictures of the tools used for roughing and finishing operations, after machining one part under the process parameters of Test 3. Even for the heaviest cutting conditions, the tool edges remain sharp; slight amounts of wear on the flank face can be detected, with moderate adhesion phenomena of workpiece material on the rake face. The tool wear values are away from the average flank wear tool-life criterion of 0.3 mm recommended by the ISO 3685 standard for tool-life testing with single-point turning tools. As expected, when reducing the process parameters, tool wear is smaller.

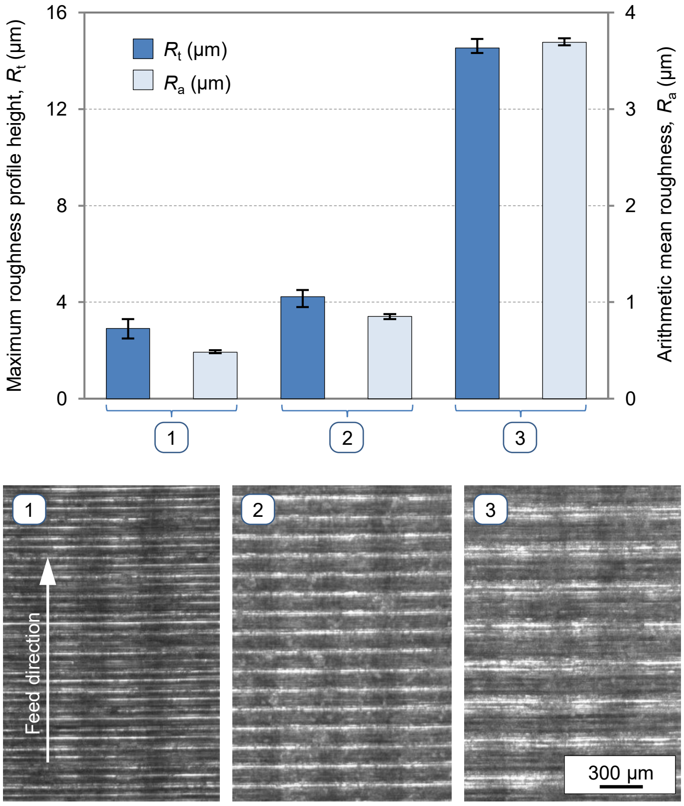


Figure 12. Surface roughness results. Finishing conditions 1-3 refer to Table 1.

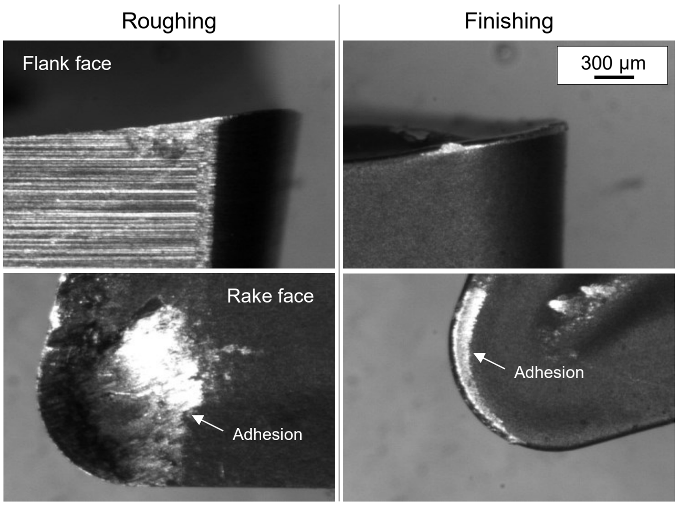


Figure 13. Tool wear results in turning for Test 3.

The energy due to machining was calculated by adopting the process parameters of Test 3 for roughing, and of Test 2 for finishing. This combination allows to significantly reduce the cycle time (and, therefore, the consumption of energy) in roughing, without causing excessive tool wear. Also, a good compromise between energy consumption and surface roughness was achieved when finishing. More in detail, the cutting time t_c was 1.5 min (1.0 min for roughing plus 0.5 min for finishing), and the energy consumption can be inferred by Figure 10 for both the manufacturing phases. The non-productive time t_{np} (i.e. for the substitution of the workpiece/semi-manufactured part) was hypothetically and conservatively assumed to be equal to 1 min (Figure 14). The energy consumption due to non-machining operations was computed multiplying the non-productive time t_{np} by the idle power of the machine, which was measured to be 1 kW. The energy required for the lubricoolant production was neglected, while the energy needed to circulate the lubricoolant within the machine tool is accounted in the machining contribution.

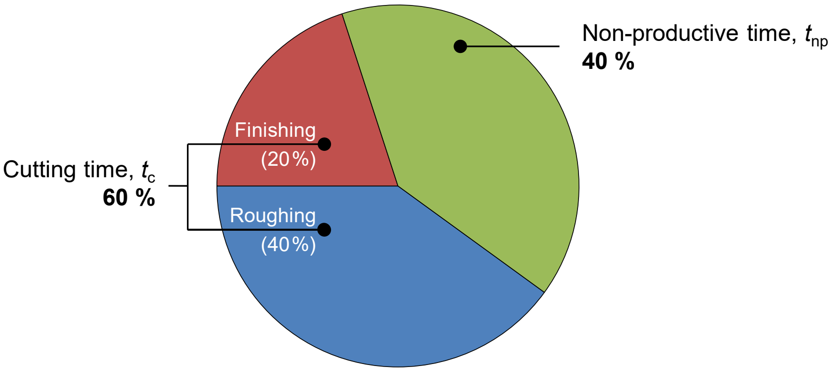


Figure 14. Time shares for machining.

As far as the energy embedded into the material is concerned, it is worth pointing out that the chips are a type of scraps challenging to recycle. Actually, recycling chips by traditional remelting procedure can cause relevant permanent material losses. In fact, light gouge scraps, characterized by a high surface-to-volume ratio, tend to float on the surface of the melt, causing significant oxidation losses. Researchers have demonstrated that, material losses in the case of chips recycling can be as high as 15-20% (Xiao et al., 2002; Van Geertruyden, 2005; Beherens et al., 2014). To properly take into account such aspect, two different recycling yields were considered for the bulk component and for the chips. In particular, for the bulk aluminum part a 5% of metal loss was estimated, whilst a recycling yield equal to 85% was assumed for the chips produced during the machining process.

The energy to manufacture the cutting inserts was included in the model. Even if it’s not a direct energy consumption of the machining process, it influences the overall energy of the system, being one of the inputs to the process itself. Literature still lacks specific information about energy footprint of tooling. Taking into account the energy embodied in the tool material and the energy for its manufacture, data presented by Dahmus and Gutowski (2004), and adopted by Rajemi et al. (2010), were used as reference. In particular, a total energy equal to 5.3 MJ per each insert was considered. The details of the energy consumption for a machined part belonging to a batch-size equal to 100 are reported in Figure 15, assuming to produce the entire batch without replacing the tools.

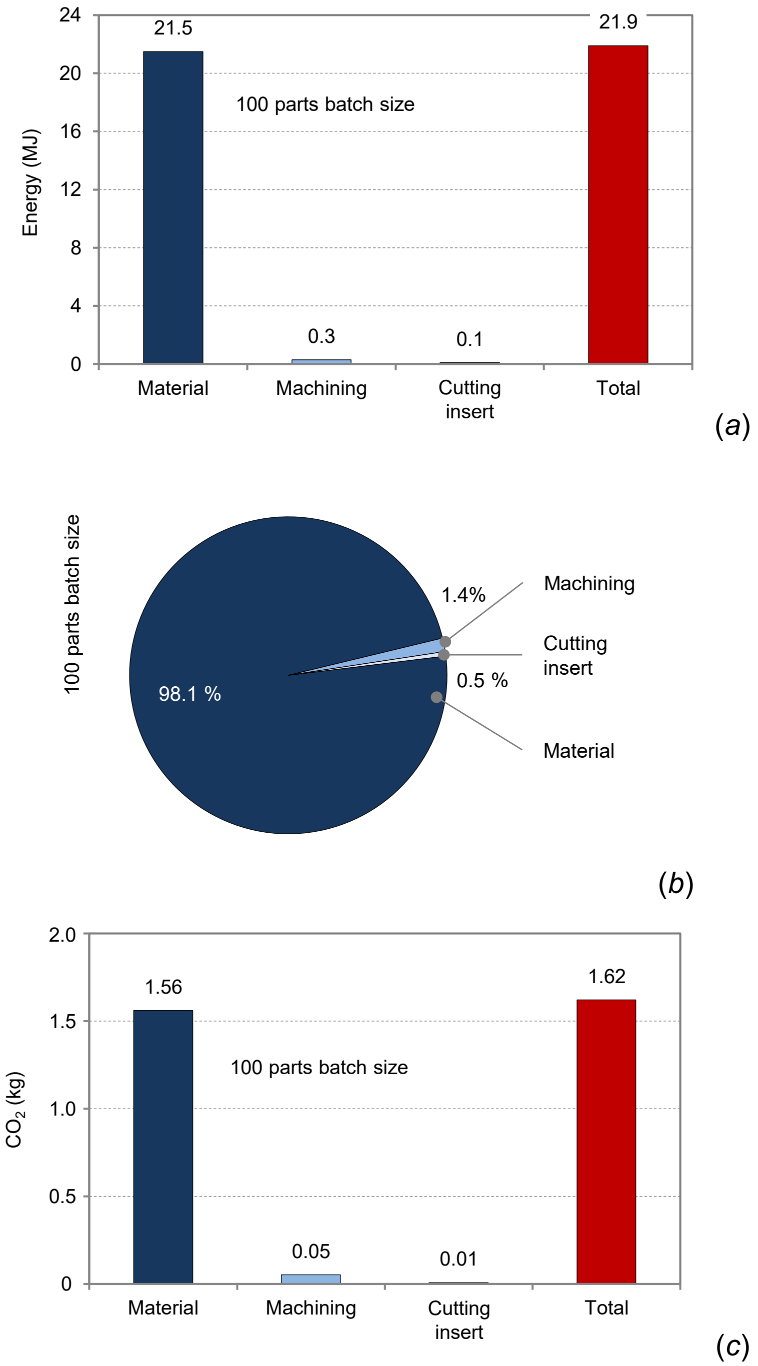


Figure 15: Energy consumption (*a*), energy share (*b*) and and CO_2 emissions (*c*) to machine a single part belonging to a batch-size of 100.

Since each tool has two cutting edges, this hypothesis implies a tool life T_L of 50 min and 25 min for the roughing and the finishing operation, respectively. The rate of tool wear depends on process parameters (Bhushan et al., 2010), and might vary significantly throughout the lifespan of the cutting tool. Therefore, different scenarios for the tool change were considered. As resumed in Table 4, the expected tool life T_L was ranged from 12.5 to 50 min, and it was assumed to be the same for both the cutting inserts. Even in the worst case, for the production of a part (in a batch size of 100) the contribution due to the cutting inserts is less than 1.5 % of the total energy consumption, which slightly increases from 21.9 MJ to 22.1 MJ with a more frequent tool change. Moreover, the benefits deriving by the recycling of the cutting tool materials were not taken into account in this research, due to the lack of specific information. As it can be noticed, despite the considered scenario for the tool change, the energy consumption due to material production is the dominant factor, and it accounts for around 98% of the total energy consumption.

Table 4. Energy consumption in machining as a function of the tool change. Batch-size is equal to 100.

	Expected tool life, T_L (min)		
	12.5	25	50
Insert(s) needed for roughing	4	2	1
Insert(s) needed for finishing	2	1	1*
Energy due to cutting inserts, per each part (MJ)	0.32	0.21	0.11
Total energy consumption, per each part (MJ)	22.1	22.0	21.9
Percentage contribution due to cutting inserts (%)	1.4	1.0	0.5

* *Note*: only a single cutting edge is used

5 Comparative analysis and results discussion

Analyzing all the results reported in the previous sections it is possible to state that, as the environmental impact is concerned, the energy consumption related to the material life cycle is the dominant influencing factor. For the machining process, the impact of the energy related to material production and recycling accounts for approximately the 98% of the whole energy consumption (Figure 15). Such result is due to the peculiarity of the machining process, which proceeds by progressively removing material. Therefore, the machining approach consumes an higher amount of material than the forming process, which is basically a mass conserving one. Figure 16 reports the comparison of the energy audits for the two processes in the case of a 100 parts batch size. To better highlight the role of the material, all the environmental influencing factors related to the pure manufacturing steps (forming, heating system and die manufacturing for the forming process; machining and insert manufacturing for the turning process) have been clustered under the item labeled "Manufacturing". It is possible to notice how the larger amount of material consumed by the machining process badly affects the whole environmental performance. In fact, the machining process requires an additional energy amount equal to 6.2 MJ. On the contrary, if the analysis is focused only on the manufacturing step, the forming process consumes an higher amount of energy (4.1 MJ versus 0.5 MJ). This outcome can be explained by considering that the press requires more energy than the lathe, and also the heating systems have to be included for the forming approach.

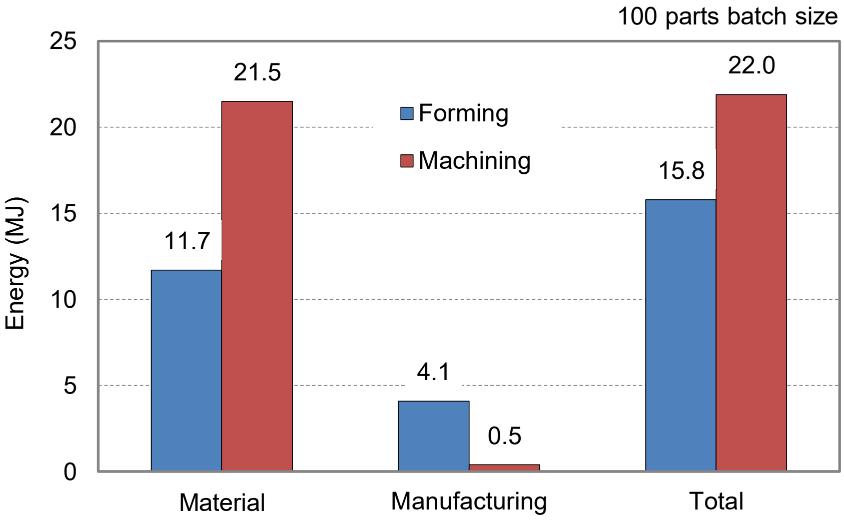


Figure 16. Comparison of the energy audits for the two considered processes in the case of a component belonging to a 100 parts batch size.

Moreover, the tooling plays a different role in the two processes. In the forming one, the tool manufacture has a relevant role in the environmental impact. In particular, for the case of 100 parts batch size, the tools share is equal to 5% (Figure 8), and the relevance increases with the decreasing of the batch size, becoming the most affecting factor in the case of a batch size equal to 10 (Figure 9). For the machining approach, the influence of the tooling is much less relevant, becoming almost negligible as shown in Figure 15. With respect to Table 4, a tool life T_L of 25 min was assumed to compute the results presented in Figures 16 and 17.

In order to get a clear picture of the environmental performance of the two analysed manufacturing approaches, a comparative analysis at the varying of the batch size is necessary. In Figure 17 the results for both the technologies are reported. The higher is the impact of the tool manufacturing, the more evident is the decreasing trend of the energy consumption per each manufactured part. It is possible to notice that, for a limited batch size (less than 17 parts), the machining process is the energy efficient solution. Actually, for low production volumes, the less material usage characterizing the mass conserving approach does not justify the energy consumption related to the die and punch manufacturing. On the contrary, at the increasing of the batch size, the die manufacturing impact is progressively neutralized and, as a consequence, the forming process becomes the greener production technology.

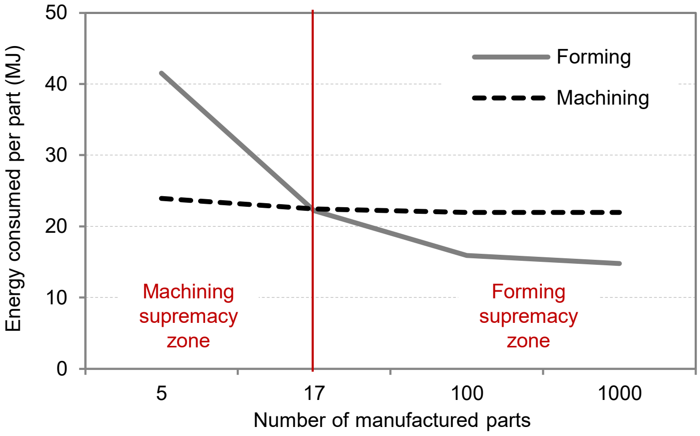


Figure17. Comparative analysis of the energy consumption per part at the varying of the batch size.

The obtained results at the varying of the batch size reproduce the trend obtainable if the economic point of view is considered. Actually, it is well know that forming processes, such as hot-extrusion, are economically profitable for large batch sizes, since the capital investment in equipment and tooling is very high. Nowadays such conclusion has to be evaluated and demonstrated also from the environmental/sustainability point of view. This paper represents a first study to increase the awareness about such aspect. It is worth pointing out that the proposed methodology, along with the background idea of the paper, aim at encourage the scientific debate about the necessity to analyze and compare different ways to shape material.

In addition, the analysis can be affected by the change in product characteristics. Beside the batch size itself, the material and the shape could strongly influence the results. A systematic study at the varying of such parameters would help to identify the most relevant environmental influencing factor.

The ecological properties strongly differ at the varying of the used metallic material. In particular, the primary production embodied energy as well as the embodied energy for recycling can noticeably change. The worsening of the material's ecological properties could badly affect a manufacturing strategy characterized by an higher amount of wasted material.

Furthermore, the shape of the component affects the process engineering. An increase of the product shape complexity could require more than one forging step, causing a wider tooling material usage. For the machining process, a complex product shape could lead to an increase of the machined-off materials with a straightforward bad impact on the environmental performance. The crossed effect of the three most influencing factors (material, product shape and batch size) has to be considered, and a systematic study at the varying of such factors would help to create the proper knowledge base to select the greenest technology case by case. The proposed methodology, therefore, could be applied to better understand the most suitable material shaping approach at the varying of the production scenario.

6. Conclusions

As long as the technological feasibility of a given process is guaranteed, processes minimizing resource and energy consumption have to be selected to manufacture a given part. The research here proposed aims at analyzing different production routes, i.e. two different ways to shape metal components: mass conserving (forming processes) and subtractive approaches (machining processes). The paper presents a starting attempt to tackle the knowledge gap in terms of comparative manufacturing analysis, since such kind of studies are fundamental in order to identify energy and resource efficiency manufacturing strategies. The environmental performances of forming and machining were compared by quantifying, collecting and modeling the energy and the resource flows to manufacture a simple mechanical part made of an aluminum alloy.

A LCA based approach, able to take into account the environmental burden of different product life-cycle phases, was developed considering the material production, the manufacturing steps and the end-of-life phase, for both the analyzed technologies. Furthermore, in order to provide the reader with more generic guidelines, an analysis at the varying of the batch size was performed, and for each scenario the energy consumed per each manufactured part was quantified.

For the analyzed case study, the dominant factor of its life cycle is related to the material production. In fact, even if the credit deriving from the recycling was considered, material-related (either for the product or for tooling) energy consumption is always the most affecting factor. The energy material share became completely dominant for the machining approach, since it accounts for about the 98% of the total energy consumption. Despite such statement, the subtractive approach cannot be a-priori rejected. Actually, the developed analysis at the varying of the batch size shows that, it is not possible to state that one approach is better in absolute terms. On the contrary, the batch size has to be taken into account because the machining approach shows better performance if smaller (fewer than 17 parts) production volumes are considered.

In the present paper, a methodology containing a detailed life cycle inventory for an aluminum component and the role of the several inputs (electric energy, material consumed, heating system) are analyzed and quantified. The research aims at providing the reader with a methodology able to thoroughly analyze the environmental impact of a given processes, and to better compare different manufacturing strategies. The methodology allows to highlight the peculiarities of each approach, and it is replicable on whichever process and material. The noteworthy aspects characterizing the proposed methodology can be summarized as it follows:

- it takes into account both primary energy as well as recycling embodied energy;
- it is a thorough LCI at unit process level;
- it accounts for material wasting;
- it diversifies the recycling process losses at the varying of the scrap feature;
- it includes an analysis at the varying of the batch size.

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REFERENCES

Ashby M. F.,2012. Materials and the Environment, Butterworth Heinemann/Elsevier.

Altan T., Ngaile G, Shen, 2005 G. Cold and Hot Forging Fundamentals and Applications,. ASM international, ISBN: 0-87170-805-1

Aurich, J.C., Linke, B., Hauschild,M., Carrella, M., Kirsch, B,. 2013. Sustainability of abrasive processes, CIRP Ann. Manuf. Technol. 62, 653–672.

Balogun, V. A., Mativenga P. T., 2013. Modelling of direct energy requirements in mechanical machining processes. J. Clean. Prod. 41,179-186.

Baumers, M., Tuck, C., Wildman, R., Ashcroft, I., Rosamond E., Hague R., 2012. Transparency Built-in Energy Consumption and Cost Estimation for Additive Manufacturing. J. Industrial Ecology, 17, 418-431.

Behrens B., Frischkorn C. , Bonhage M., 2014. Reprocessing of AW2007, AW6082 and AW7075 aluminium chips by using sintering and forging operations Prod. Eng. Res. Devel. DOI 10.1007/s11740-014-0542-2

Bhushan, R. K., 2013. Optimization of cutting parameters for minimizing power consumption and maximizing tool life during machining of Al alloy SiC particle composites. J. Clean. Prod. 39, 242-254.

Bhushan, R.K, Kumar, S., Das, S., 2010. Effect of machining parameters on surface roughness and tool wear for 7075 Al alloy SiC composite, International Journal of Advanced Manufacturing Technology, 50 (5-8), 459-469.

Campatelli, G., Lorenzini, L., Scippa, A. 2014. Optimization of process parameters using a Response Surface Method for minimizing power consumption in the milling of carbon steel. J. Clean. Prod. 66,309-316.

Carbon Trust,2011. Industrial Energy Efficiency Accelerator – Guide to the metal forming sector, 2011. available on www.carbontrust.com

CO_2PE! - Cooperative Effort on Process Emissions in Manufacturing, last visited 06/03/13, www.co2pe.org

Dahmus, J., Gutowski, T. 2004. An Environmental Analysis of Machining. Proceedings of the 2004 ASME International Mechanical Engineering Congress and RD&D Exposition, Anaheim, California, USA, November 13-19

Davoodi B, Tazehkandi A. H., 2014. Experimental investigation and optimization of cutting parameters in dry and wet machining of aluminum alloy 5083 in order to remove cutting fluid. J. Clean. Prod.68, 234,242

Devoldere, T., Dewulf, W., Deprez, W., Willems, B., & Duflou, J. R., 2007. Improvement potential for energy consumption in discrete part production machines. In Advances in Life Cycle Engineering for Sustainable Manufacturing Businesses, 311-316, Springer London

Diaz, N., Helu, M., Jayanathan, S., Chen, Y., Horvath, A., Dornfeld, D., 2010, Environmental Analysis of Milling Machine Tool Use in Various Manufacturing Envrionments, Proceedings of the IEEE International Symposium on Sustainable Systems and Technology (ISSST), Arlington, USA, 1-6.

Díaz-Tena, E., Rodríguez-Ezquerro, A., López de Lacalle Marcaide, L.N., Gurtubay Bustinduy, L., Elías Sáenz A., 2014. A sustainable process for material removal on pure copper by use of extremophile bacteria, Journal of Cleaner Production, http://dx.doi.org/10.1016/j.jclepro.2014.01.061

Dittrich, M. A., Gutowski, T., G, Cao, J., Roth, J.T Xia, Z. C., Kiridena, V., Ren, F., Henning, H., 2012. Exergy analysis of incremental sheet forming. Prod. Eng. Res. Devel., 6: 169-177

Duflou, J.R., Sutherland, J., Dornfeld, D., Herrmann, C. Jeswiet, J., Kara, S., Hauschild, M., Kellens, K., 2012,. Towards energy and resource efficient manufacturing: A processes and systems approach, CIRP Annals - Manufacturing Technology. 61/2, 587-609.

Granta's CES EduPack: Teaching Resources for Materials and Process Education. Available online: http://www.grantadesign.com/education/ (Accessed on 21/09/2014)

Gutowski, T. 2009. Design and Manufacturing for the Environment. in K. H. Grote, E.K. Antonsson (Eds.), Handbook of Mechanical Engineering, Springer-Verlag, pp. 853–866,

Gutowski, T., Dahmus, J., Thiriez, A., 2006. Electrical energy requirements for manufacturing processes. In: 13th CIRP International Conference on Life Cycle Engineering, Leuven, Belgium, 623-628.

Hammond G., Jones C., 2010. Inventory of carbon and Energy (ICE), Annex B: how to account forrecycling a methodology for recycling, The University of Bath, Bath, UK.

Ingarao, G., Di Lorenzo, R., Micari, F., 2011. Sustainability issues in sheet metal forming processes: an overview. J. Clean. Prod.,19, 337-347.

Ingarao, G., Vanhove, H, Kellens, K, Duflou, J. R., 2014. A comprehensive analysis of electric energy consumption of single point incremental forming processes. J. Clean. Prod.67 ,173-186.

International European Agency (IEA 2013) CO2 EMISSIONS FROM FUEL COMBUSTION Highlights (2013 Edition)

Jeswiet, J., Kara, S.,2008. Carbon emissions and CES™ in manufacturing CIRP Annals - Manufacturing Technology. 57,17–20

Kara, S., Li, W., 2011. Unit process energy consumption models for material removal processes. CIRP Annals - Manufacturing Technology, 60, 37-40.

Kellens,K. 2013. Energy and resource efficient manufacturing Unit process analysis and optimisation. Phd Thesis, Department of Mechanical Engineering Centre for industrial management traffic and infrastructure, KU LEUVEN,

Kellens, K., Dewulf, W., Overcash, M., Hauschild, M.Z., Duflou J.R., 2012. Methodology for systematic analysis and improvementof manufacturing unit process life-cycle inventory (UPLCI)-CO2PE! initiative (cooperative efforton process emissions in manufacturing). Part 1: Methodology description. Int. J. Life Cycle Assessment, 17, 69-78.

Kellens, K.,Dewulf, W.,Ingarao, G.,Duflou, J.(2014).Energy Efficiency of Sheet Metal Working Processes - Where do we stand today?.New Developments in Sheet Metal Forming. Int. Conference on New Developments in Sheet Metal Forming.Stuttgart,12-14 May 2014.

Kellens, K., Renaldi, Dewulf, W., Kruth, J.P., Duflou, J.R., 2014. Environmental Impact Modeling of Selective Laser Sintering Processes, accepted for publication in the Rapid Prototyping Journal.

Kervick,R., Blue, C. A., Kadolkar, P.B. , Ando, T., Lu, H., Nakazawa, K., Mayer, H., Mochnal, G.2006. Enhancement of Aluminum Alloy Forgings through Rapid Billet Heating, Final Technical Report, available on http://www.osti.gov/bridge.

Kuram, E., Ozcelik, B ., Bayramoglu M., Demirbas, E., Simsek ,B. T., 2013. Optimization of cutting fluids and cutting parameters during end milling by using D-optimal design of experiments. J. Clean. Prod . 42, 159-166

Lawal S. A., Choudhury I. A., Nukman, Y.,2014. Evaluation of vegetable and mineral oil-in-water emulsion cutting fluids in turning AISI 4340 steel with coated carbide tools. J. Clean. Prod. 66, 610-618.

Lawal S., Choudhury I.A. , Nukma Y., 2013. A critical assessment of lubrication techniques in machining processes: a case for minimum quantity lubrication using vegetable oil-based lubricant. J. Clean. Prod. 41 , 210.221

Le Bourhis F., Kerbrat,O., Hascoet J., Mognol, P.,2013. Sustainable manufacturing: evaluation and modeling of environmental impacts in additive manufacturing. Int. J. Adv. Manuf. Technol . 69,1927–1939

Li L., Yan J., Xing Z., 2013. Energy requirements evaluation of milling machines based on thermal equilibrium and empirical modelling. J. Clean. Prod. 52, 113-121.

Mayyas T. A., Qattawi A., Mayyas A. R., Omar M. A., 2012. Life cycle assessment-based selection for a sustainable lightweight body-in-white design. Energy. 39, 412-425.

Milford R. L., Allwood J. M., Cullen, J. M., 2011. Assessing the potential of yield improvements, through process scrap reduction, for energy and CO_2 abatement in the steel and aluminum sectors. Resources, Conservation and Recycling 55, 1185– 1195.

Morrow, W.R., Qi, H., Kim, I., Mazumder, J., Skerlos, S.J., 2007. Environmental aspects of laser-based and conventional tool and die manufacturing. J. Clean. Prod.15, 932-943.

Narita, H., Kawamura, H., Horihisa,T, Chen, I. fujimoto, H, Hasebe T.,2006. Development of prediction system for environmental burden for machine tool operations. Jsme international journal, 49/4,

Nava P., 2009. Minimizing Carbon Emissions in Metal Forming, Phd thesis. Department of Mechanical and Materials Engineering ,Queen's University Kingston, Ontario, Canada, December 2009.

Paraskevas, D., Kellens, K., Renaldi, Dewulf, W., Duflou, J. R., 2012. Resource Efficiency in Manufacturing: Identifying Low Impact Paths, Proceedings of the 10th Global Conference on Sustainable Manufacturing (GCSM2012) ,271-276.

Rajemi, M.F., Mativenga, P.T., Aramcharoen, A., 2010. Sustainable machining: selection of optimum turning conditions based on minimum energy considerations. J. Clean. Prod. 18, 1059–1065.

Santos, J. P., Oliveira, M., Almeida, F. G., Pereira, J. P., Reis, A., 2011. Improving the environmental performance of machine-tools: influence of technology and throughput on the electrical energy consumption of a press-brake. J. Clean. Prod. 19, 356-364.

Serres, N., Tidu, D., Sankare, S., Hlawka. F., 2011. Environmental comparison of MESO-CLAD process and conventional machining implementing life cycle assessment. J. Clean. Prod. 19, 1117-1124.

Sharma, J., Sidhu, B.S., 2014. Investigation of effects of dry and near dry machining on AISI D2 steel using vegetable oil. J. Clean. Prod. 66, 619-623.

Van Geertruyden, W.H., Prescott, C.A., Misiolek, W.Z., Peterson. R., 2005. Evaluation of Light Gauge Aluminum Scrap Remelting After Consolidation via the Extrusion Process Light Met. Age Band, 63,14–18.

Winter, M., Li, W., Kara, S., Herrmann. C., 2014. Determining optimal process parameters to increase the eco-efficiency of grinding processes. J. Clean. Prod. 66, 644-654.

Xiao, Y., Reuter, M.A., 2002. Recycling of distributed aluminium turning scrap, Minerals Engineering, 15/1(1),963-970

Yan, J., Li, L., 2013. Multi-objective optimization of milling parameters - the trade-offs between energy, production rate and cutting quality. J. Clean. Prod., 52, 462-471.

Zhao, F., Bernstein, W. Z., Naik, G., Cheng, G. J., 2010. Environmental assessment of laser assisted manufacturing: case studies on laser shock peening and laser assisted turning. J. Clean. Prod. 18, 1311-1319.