Approach to Reduce the Environmental Impact of a CNC Manufactured Product in the CAD Phase

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Abstract. CO_2 neutrality is an important goal for the upcoming years. It is necessary to ensure that greenhouse gases are emitted as few as possible, particularly for the development of new products. The most important decisions, with impact on the sustainability, are already made by the product designer during the virtual product development phase, such as raw material requirements, selected manufacturing process or thermal and surface treatments. Especially in the case of ablative processes (CNC), raw material has a major impact on the calculated carbon footprint of products.

In order to minimize the emissions of greenhouse gases in the virtual product development phase already, this paper presents an approach to provide assistance for the product designer regarding the ecological impact of his decisions. For this purpose, Life Cycle Assessment (LCA) methods are directly integrated into the CAD software. During the design process, the expected CO_2 equivalents of the largest influencing factor - the raw material - can be displayed which is observed for most cases of metal material. In addition, the savings potential for reducing the blank volume or changing the raw material is shown and a suggestion is made.

Keywords: Life Cycle Assessment · Sustainable Product Development · CAD · CAM · Assistance System · Multi Scenario Analyzer

1 Introduction

In this day and age, climate protection is one of the most difficult challenges. To master this challenge, the European Commission determines greenhouse gas neutrality for the European continent up to the year 2050. This overriding goal is known as the European Green Deal (EGD) and was introduced in December 2019 [1]. With this key project, there are two main tools in the European Union (EU) to reduce gashouse gases: One of them is the EU climate protection requirement and the other one is the EU emissions trading. Within the trading system, there is a cap of the overall greenhouse gas emissions which will be scaled down year by year. This affects energy-intensive companies, particularly in the energy, production industry and air traffic sectors. These involved sectors have to

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break new ground to reduce greenhouse gas emissions in view of keeping the limits that are set by the EU. Especially when it comes to a new product design, there should be an understanding which effect a new product has on the environment.

The engineering view of a typical product lifecycle can be divided in the phases product development, production, utilization and different end of life scenarios, such as recycling or disposal. Every phase has an impact on the environment but only the first phase of the product development can affect the emissions of all the following other phases. Usually the product developer has not a great knowledge about the different following scenarios of the product's lifecycle and the impact of his decisions. This begins with the choice of the raw materials and the production processes. Even if the product in the product development phase is just a digital model, the needed raw material for production can be seen as a degree of freedom. However, the production of the raw material has so many possible parameters that the product developer has no possibility to quantify the impact of his decisions.

When it comes to quantifying the impact of products on the environment Life Cycle Assessment (LCA) is a widely used method [2]. In the past decades, a variety of LCA methods and indicators on the environmental impact have been developed. Every single knot of the supply chain of a product can be quantified and converted into greenhouse gas equivalents or other factors. With this opportunity, it is possible to track the greenhouse gas impact, for example the mining of raw material or the production of energy. LCA tools are often standalone, complex applications that are used by experts. However, they are not designed to be used in the product development process. The software requires extensive knowledge of information that is missing in the design process [3]. Moreover, the LCA approach is not user friendly and too complex to use it in an easy way [4].

When it comes to metal materials and abrasive processes, the choice of the raw material has a significant impact on the overall environmental footprint of the product. An example of the impact can be seen in the evaluation of the production of a threading tool where the total amount of the CO_2eq for the complete production is 1.493 kg. The raw material has an amount of 0.76 kg CO_2eq which is 51% of the sum [5]. In this case, the biggest lever to minimize the carbon footprint is the raw material. By designing a new product for CNC milling, the product developer defines the required blank volume at the very first step with the design software. This blank volume is the base for the CAM simulation and the required raw material in the following milling phase.

In this paper an approach for a product developer assistance system for CNC manufactured products is presented. This assistance system aims to give user friendly information of the raw material impacts on the environment in the CAD phase even before CAM is performed and the concept is consequently independent of a machine strategy. Therefore, the methods of LCA are directly integrated in the CAD software and suggestions to reduce the environmental impacts are given.

2 Current Use of LCA Methods and Tools

LCA methods and tools are used in various ways to reduce the environmental impact in the manufacturing industry. They can be divided into traditional application after production, usage in the production process and usage in product development. The traditional application includes standalone LCA software after the product was produced.

Commonly used tools for LCA evaluation with huge databases themselves are SimaPro or GaBi [6, 7]. The scope can be classified into "cradle to gate" analysis or "cradle to grave" analysis with the aim to summarize the environmental impacts for internal or external use before the product is sold. In production processes there are diverse analyses and approaches aiming on the reduction of resource consumption, for example of machine components [8]. Moreover, there are some approaches that uses LCA methods in the product development phase. One of them shows that an integration of LCA methods into structural optimization strategies for eco-design can support designers to lower the impact of products in the design phase already [9]. A complete integration of an LCA tool into CAD software has already been developed by Dassault Systèmes with the sustainability tool for the CAD software SolidWorks [10]. After designing a product, a CAD user can analyze different environmental impacts of the product by using a dropdown menu with different scenarios. Different materials are included and a report can be exported. An approach to integrate LCA in the CAD/CAE environment is given by Fang et al. [11]. Besides the environmental analysis of CNC machine tools, a sustainable design index (SDI) is developed to show energy consumptions, costs, CO_2 emissions and different design strategies with integrated analysis.

The existing approaches are complex to use and great knowledge about the lifecycle of the product is assumed. Even if the designer has knowledge in using LCA methods, it takes time to apply existing tools and software plugins which is often not practicable. This results in a need for an easy to use assistance system for designers.

3 Integration Method into CAD Phase

The developed assistance system for product developers can be integrated into the graphical user interface (GUI) of the CAD software and so be called easily as a new feature or function in the design process. In this approach, the used CAD software is Siemens NX 1926 but it can also be adapted for other CAD programs. The feature is developed in a way that it can be used in every step of the design phase regardless of level of detail.

The assistance system consists of three parts. The first part is called "simplifier" and its function is picking the relevant information out of the CAD model for the further software processing and provide the final results. By activating the feature, the dimensions of the model are transmitted into the assistance system. Details of the model are simplified and the required blank volume for a CNC production is calculated. This could be a block or a cylinder with offsets fulfilling geometric tolerances and clamping device attachments. Usually, the blank volume is created later by the designer during CAM programming. In this case, the required blank volume is created automatically by the assistance system by calculating the boundaries and adding the offsets. After the simplification of the CAD model, the required information for a LCA is transferred to the second module of the assistance system.

The second part is called "multi scenario analyzer". This module creates different LCA scenarios and contrasts these with regard to their environmental impact. The module replaces the complex and time-consuming user inputs into a LCA software tool and considers different points of view. No experience is required for using the automatic calculation. Inputs for the multi scenario analyzer are the blank volume dimensions, metal material information and current (geo-)location of the user. With these inputs, a variation of different production scenarios is created based on expert knowledge.

A basic material for CNC milling is aluminum. To produce a block of aluminum different steps must be carried out which results in an enormous number of input parameters. To get to the final production step which represents a production of an aluminum block, five different inputs can be figured out. The inputs are aluminum fluoride, produced anodes from coke and bauxite as well as electricity and process heating. Every block has his own input until the materials are directly consumed as natural assets such as air, water or raw materials. To show the complexity of the aluminum block production scenario, the five inputs of the aluminum fluoride block are listed: bauxite, quicklime, hexafluoro silicic acid, sodium hydroxide and process heating from two different sources are needed to produce the aluminum fluoride. Outputs of the production step are the aluminum fluoride and production waste which is not displayed. Summed up for the whole process, over 2600 sub processes (inputs and outputs) are found only for this aluminum production scenario.

This specific production scenario is handed over to the third part of the assistance system. The main function in this part is the performance of the LCA. The common results of an LCA is the calculation of different environmental impacts. A variety of impact assessment methods can be used for this purpose. The methods address different impact categories. Examples are the "Baseline model for 100 years, based on Intergovernmental Panel on Climate Change 2013 (IPCC)" which considers the impact categories climate change – overall, biogenic or land use and transformation, the method "ReCiPe" which has different impact categories such as formation of photochemical ozone, eutrophication – freshwater or marine and the method "CML 2002" with impact categories resource use and fossil [12]. One of the most used methods in practice is the eco-indicator 99 [13]. The midpoint approach includes 11 impact categories which can be classified in the three main categories human health, ecosystem quality and resources. There are different units in the methods in relation to their impact category. The focus of the assistance system is to give an easy to use and easy to understand environmental impact calculation. Therefore, the method "ReCiPe Midpoint (H)" is selected because of the direct calculation of the climate change impact and the transparent implementation [14]. There are three different calculations for this method. The hierachrist (H) calculation fits best for the assistance system. It is based on policy principles regarding a timeframe of 100 years for global warming. The calculation creates the CO_2 equivalents (CO_2eq) of the final product. This unit is used in the assistance system but it is also possible to export a full report about the other impact categories such as different ecotoxicities in kg 1.4 dichlorobenzene (1.4-DB) eq or terrestrial acidification in SO_2eq. After the environmental impact calculation of the production scenario, the results are returned to the multi scenario analyzer. The tool is then going to find the optimal scenario relating to the environmental impact by variation of parameters and completely different scenarios. Therefore, established optimization methods are used. The most applied method in literature to integrate LCA optimization is the multi-objective optimization where the Pareto set is generated by an ε-constraint method [13]. The calculated optimum is then handed over to the simplifier. Here, the calculation units are prepared for the graphical display in the CAD software plug-in.

4 Case Study

In this section, a practical execution of the support in the CAD pre-phase (before CAM simulation) is shown. Therefore, it is not necessary to have any knowledge in CAM simulation. The designer can operate the assistance system in his familiar feature-modeling environment. The investigated validation object is a part of a pneumatic cylinder which is manufactured in CiP - Center for Industrial Productivity (Process Learning Factory) at the Technical University Darmstadt by CNC milling. It is the top cover of the pneumatic cylinder assembly and can be seen on the left side in Fig. 1.

Inside the CAD software, the designer can activate the assistance system as a new feature or function in the main toolbar. The used software in this case is Siemens NX 1926. After activating the new feature, the model is analyzed by the simplifier and the relevant dimensions of the complete model are merged into a volume in which the hole model fits. This can be either a cylinder or a block volume. Both are created first and the volume with the smaller content is selected afterwards. This represents the minimum of the required blank volume for the CNC milling and a value of 52737.50 mm^3 was determined. An offset off 5 mm in every direction is added which fulfills typical geometric tolerances for the milling process and clamping device attachments. The offsets in the different directions can be changed manually as well as the suggested positions of the clamping devices.

The assistance system checks now if there is a material assigned to the CAD model. In this case, an aluminum material without further details, such as alloys, is assigned in the CAD system. As a next step, different aluminum production scenarios will be considered. If no material is assigned, the tool checks different production scenarios for typical CNC metal materials. The first production process for aluminum depending on the user's location is created. The groundwork for this scenario is a pre-defined process in the ProBas + database. The LCA is performed with the ReCiPe Midpoint hierachist (H) method. The first result is a climate change impact of 32.32 kg CO_2eq for the raw material with the required dimensions for the pneumatic cylinder top cover. After four more calculations of completely different aluminum production scenarios, a minimum is found at 1.34 kg CO_2eq. The high difference between the values is due to different variations in energy production in the different aluminum production scenarios. This value is transferred back to the CAD plug-in. Moreover, the minimum volume is shown and a report can be created for the other environmental impacts such as human toxicity or freshwater eutrophication of the detailed assumed production scenario. If no detailed report is required, the CO_2eq value can be stored in the CAD model as a product manufacturing information (PMI) as is it can be seen in Fig. 1.

The minimum needed raw material block for the whole model can be seen in the middle. Typically, a raw material block has some kind of offset regarding to defined products by a manufacturer or attachments in the CNC machine. Moreover, geometric tolerances have to be fulfilled in the following manufacturing process. A minimum of 5 mm in every direction is a common offset to meet these requirements. The offset has a significant impact of the CO_2eq value for the raw material. The value increases by 127% to 3.04 CO_2eq.

A second feature of the assistance system is to give a recommendation to lower the environmental impact of the model. This could either be a change of material or

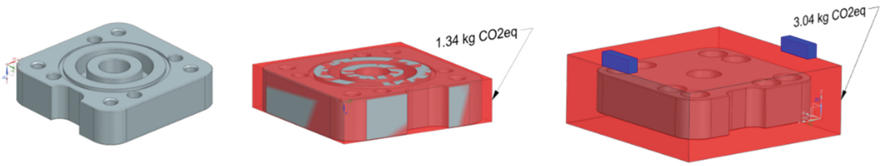

Fig. 1. Top cover of the pneumatic cylinder assembly (left), CO_2eq of a minimum required aluminum block for the top cover without offset (middle) and with 5 mm offset and symbolic clamping attachments (right)

a change of dimensions. A minimum impact of the aluminum production was already determined. A suggestion for changing the material is given only if the material has not been specified before. For a block volume, the model is analyzed and different possible reductions are considered. One possibility is given in Fig. 2:

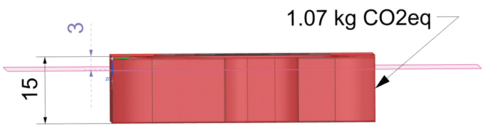

Fig. 2. Suggestion for a 3 mm reduction in height of the original CAD model to reduce CO_2eq

The originally designed top cover has a height of 15 mm. The assistance system displays the reduction of the CO_2 equivalents if the general height of the CAD model is reduced. In this case, a reduction of 3 mm is shown. The CO_2 equivalents are proportional to the outer dimensions of the minimum box, so that the value decreases by 25 percent to 1.07 kg CO_2eq. When the offset of 5 mm is also considered, a reduction by 13 percent to 2.67 kg CO_2eq is calculated. The suggested reduction of the height of the original CAD model can also be manually be changed and the impacts are shown immediately.

5 Conclusion

LCA methods are the key to quantify environmental impacts of products. By quantifying the different impacts, decision-making in the design process of products can be optimized. Therefore, the LCA methods have to be integrated in the design process to visualize the environmental impacts. The usage of LCA methods is often complex and time-consuming, so that expertise is required. In a typical design process, the designer does not have LCA methods expertise which is why it is not possible to quantify the environmental impact of his decisions. When it comes to manufactured products by CNC, it is also a common practice, that the designer is not involved in the manufacturing process at all. Consequently, the designer has no expertise in using CAM simulations for the CNC process. The presented approach combines LCA methods and CAM simulations in a way that a designer can track the impacts of his decisions in the very first phase of the CAD model. Especially designing a whole new product, the environmental impact cannot be evaluated from existing manufactured product generations. Related on findings of literature and past research projects, the raw material of an CNC manufactured product regarding metal materials has the biggest value of the environmental impact and in particular of the carbon footprint. This knowledge is used to implement an assistance system that calculates the environmental impacts and visualize the impacts as simply as possible. This leads to a designer's support without great knowledge neither in LCA calculations nor in CAM simulations. Furthermore, the assistance system is taking different production scenarios into account in order to get a minimum value of the CO_2eq. This production scenario can be shown in a detailed report, so that transparency of the LCA calculation is given. Besides the CO_2eq which represents an established value for climate change, other values can be seen in the report such as acidification or eutrophication.

In this approach, it is assumed that climate protection will be the most important goal in the upcoming years. Therefore, efforts must be made to keep the carbon footprint of new products as small as possible, even if not much information about the product is available yet. Currently, companies are faced with the conflicting goals of keeping the price as low as possible and the carbon footprint as small as possible. In certain situations, this does not go hand in hand and due to larger economic interests, the lower price is chosen. Policies in the coming years may change this towards high costs of CO_2 emissions or CO_2 equivalents and companies need to pay particular attention to the environmental impact of their decisions. In these decisions the presented approach should support a designer in an understandable and transparent way with simple assumptions.

Although it has been shown in past projects and literature that the raw material has the greatest influence factor in CNC production of metal materials, this still needs to be validated in further studies, especially in relation to the size of the product or a possible reduction of the offset. Of further interest are also the production costs, which must first be determined in order to integrate them into the model. In addition, other materials need to be investigated such as plastics. Also, the different metallic alloys for CNC milling and their post-processing needs to be balanced holistically. With regard to the selected production scenarios, it must be noted that companies are usually limited in their choice of suppliers. On the one hand, prices can be lowered if large quantities are purchased, and on the other hand, attention must also be paid to the availability of the required material. The assumed production scenario therefore represents an ideal case for minimizing the footprint. However, a new balancing of the environmental impacts must be carried out once the supply chain has been determined.

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