Available online at www.sciencedirect.com

ScienceDirect

Procedia CIRP 120 (2023) 362–367

www.elsevier.com/locate/procedia

56th CIRP Conference on Manufacturing Systems, CIRP CMS '23, South Africa

Concept for life cycle oriented ecological assessment in tooling

Christian Lürken[a,*], Gonsalves Grünert[a], Lars Stauder[a], Sebastian Barth[a], Thomas Bergs[a,b]

[a]*Laboratory for Machine Tools and Production Engineering (WZL), RWTH Aachen University, Campus-Boulevard 30, 52074 Aachen, Germany*
[b]*Fraunhofer Institute for Production Technology IPT, Steinbachstraße 17, 52074 Aachen, Germany*

* Corresponding author. Tel.: +49 241 80-27372 fax: +49 241 80-22293. *E-mail address:* c.luerken@wzl.rwth-aachen.de

Abstract

The increasing demands of customers to use climate neutral products are leading to severe challenges for manufacturing companies in various industry sectors. The most significant issues lie in measuring and evaluating the resulting environmental impacts across the various lifecycle phases of a product. Especially for the tooling industry, it can be a decisive competitive factor, not only to measure and evaluate the environmental impact of the tool manufacturing processes, but also of the use phase of the manufactured tools. Therefore, this paper presents a concept for ecological assessment for tooling companies, taking the manufacturing phase and the use phase into account. It describes how tool manufacturers can evaluate their own processes based on material and energy inputs and outputs in order to link the environmental impacts to the manufactured product. In tool manufacturing, the digital twin is used as an essential medium for collecting ecological information and converting it into impact variables. The recorded production data from the manufacturing and use phase will be aggregated into different target dimensions: By using the target dimensions "Tool", "Tool component" and "Process" the evaluation concept can not only be used for a holistic report on environmental impacts of the manufactured products, but also be used to improve technology use and application from an ecological perspective. By adding the target dimension "Product" the use phase of the tool will be considered, in order to be able to visualize effects in which an ecologically intensive production can lead to reduction in environmental impact over the use phase. Furthermore, the target dimension "Company" is aggregating the derived data, which is necessary for the evaluation of the other target dimensions, to reporting types, such as the Greenhouse Gas Protocol or the Corporate Sustainability Reporting Directive.

Keywords: Ecological assessment; Tooling; Tool making; Evaluation System; Digital Twin

1. Introduction

In this paper, an approach for life cycle oriented ecological assessment of technical products is presented and detailed for the use case of tool making. For this purpose, the motivation for the ecological assessment is first presented and the reason for the selected use case is clarified. Subsequently, the situation in tooling is explained and the methods and objectives are outlined. Further, the concept for the ecological evaluation of technical products is presented in chapter 2 and the requirements and constraints to be taken into account are identified in chapter 3. The evaluation model for the chosen use case is explained in chapter 4 and the tool making specific target dimensions are discussed. Finally, chapter 6 presents the validation of the concept and the associated challenges for complex value creation networks.

1.1. Motivation

The sustainable transformation of the manufacturing industry is one of the great challenges of the 21st century. Due to the advancing climate crisis, societal demands are changing toward more ecologically sustainable products. Manufacturing companies must meet these demands to continue selling products in the future. [1, 2] To accelerate sustainable change,

10.1016/j.procir.2023.09.003

since 2024 the European Union has also been implementing a legally binding framework [3]. The most important ecological target for companies is currently the emission of CO_2 equivalents, which is an evaluation parameter for climate change, but is only a one-dimensional evaluation of the complex correlation of environmental effects [4]. However, even the calculation of CO_2-equivalent emissions is a major challenge to manufacturing companies [5]. They lack the necessary transparency of their processes and their material and energy consumption to detect the right levers for low-emission or even climate-neutral production [5–7].

1.2. State of the art

In applied science, there is already a large number of scientific approaches that examine sustainability in production and strive for indicator-based comparability of processes or companies. [5, 8–11] However, most approaches lack compatibility with current legal developments and detailed process evaluation based on production data. Existing reporting initiatives such as the Global Reporting Initiative or the Carbon Disclosure Project set general standards for industrial application, but lack the depth of detail for practical implementation on the manufacturing level. [12] The most widely used reporting standard for climate change is the Green House Gas Protocol, which aggregates a company's CO_2 emissions into different scopes. [10, 12] According to KAPLAN, however, this has various systematic weaknesses when applied across value chains. [4, 13] In the most recent legal framework, such as the Corporate Social Reponsibility Directive of the European Union, existing reporting standards are to be taken up, but there is no detailing on the process level in production.

Schramm's work examines different life cycle analyses of products and shows the great variance in system boundaries as well as the need for action in uniform data recording. [14] VOLLMER considers the data collection of energy and material consumption in production but does not translate this into concrete environmental impacts. [15] GRÜNEBAUM presents a cross-life cycle and process chain based approach to assessing the environmental impacts of products in his work on ecological-economic optimization by dividing the manufacturing process into process modules. [16, 17] However, this approach is not applicable to complex and variating process sequences and comes with high implementation and evaluation effort in single-part production.

Consequently, there is no scientific approach for the ecological assessment of varying process sequences that can be applied to complex value creation chains across all life phases.

1.3. Initial situation in tooling

As developer and manufacturer of manufacturing equipment, the tool shop represents the key link between product development and series production [18, 19]. In this paper, the word "tool" is used for hollow-forming manufacturing equipment for series production, while "product" refers to the item manufactured with the tool. Since a tool is used as manufacturing equipment to produce a large number of identical products, tools are usually unique items that are themselves only produced in very small quantities [18]. Due to the high technical requirements on the products to be manufactured, however, tools are high-tech products with the highest accuracy and durability requirements at the component level. Toolmaking companies must realize the complexity in single-part production, which leads to a high process chain variance. [18, 19] For this reason, the tooling industry serves as scalable example for the purpose of this paper, as the process chain variance within a tool shop can be transferred to an entire value creation network. Approaches to process evaluation in single-part production are directly transferable to serial processes, where the solution space is concretized by the specification of many framework conditions, e.g. defined process chains, thus facilitating the applicability of flexible methodologies. The tooling industry itself is characterized by small to medium-sized companies (SMEs) with internal and external market access, of which more than 80 % have less than 20 employees [20]. Furthermore, most companies can be characterized by a low degree of digitalization in manufacturing [21]. Due to the high cost pressure from Asia and Eastern Europe, the know-how-rich industry in Western Europe must develop new unique selling points [18, 19, 22]. By evaluating the ecological footprint of tool manufacturing and forecasting the environmental impact of the series production process, a decisive competitive factor can be created that makes the technological and ecological performance of the tool visible in comparison with competing products.

1.4. Method and objective

SMEs require transparency in their processes regarding productivity, quality, costs as well as environmental impact. For the manufacturing of technical products, an ecological assessment can only be reasonably evaluated, if all participants in the value creation chain report the product-specific environmental impacts in consideration of a uniform reporting framework [5]. With such an approach, it is possible to combine the resulting environmental data of the individual value creation partners in a uniform product report. This allows customers, original equipment manufacturers and other stakeholders to compare the ecological assessments of products as well as manufacturing processes. With the life cycle assessment (LCA) according to DIN 140140/44, a suitable method for the assessment of environmental impacts already exists. Nevertheless, industrial standards regarding the reported impact categories are still missing. [14, 23] Within an LCA, primary (foreground) data for the life cycle inventory (LCI) and secondary (background) data are aggregated in the evaluation method to calculate the environmental impact in midpoint and endpoint categories [24, 25]. A big advantage of the LCA is the fact that with a holistic LCI, the different impact categories can be evaluated with sufficient secondary data. This means that with the development and implementation of an automated LCA based on manufacturing data companies only need to focus the data acquisition for the LCI (if goal and scope are set), whilst the secondary data, e.g. LCI databases, and reporting standards are being developed further. Furthermore, the LCA needs to be extended by further target figures, such as ecological efficiency key performance indicators (KPIs).

Additionally to the manufacturing phase, the scope of LCAs needs to be enhanced to further life cycle stages to realize a holistic and conclusive evaluation of a product's life cycle. [17, 26] Otherwise, ecological expense in the manufacturing phase that leads to higher product durability or less environmental impact in the use phase, will not be considered by only focusing on single life cycle stages. Therefore, a life cycle oriented ecological assessment is necessary.

2. Concept of ecological assessment of technical products

For technical products, complex value creation chains are a major challenge regarding the acquisition, aggregation and exchange of life cycle data [14, 27]. A concept for ecological assessment of technical products needs to include a product environmental passport (PEP), which aggregates the reported environmental data of all participants of the product's value creation chain. This indicates for manufacturing companies that all manufacturing processes need to be recorded accordingly to the PEPs' standards and have to be aggregated on the component and product level. Therefore, manufacturing companies need to integrate the environmental impact of all manufacturing processes applied to the product into the PEP. Furthermore, for a holistic evaluation, all manufacturing equipment and used material need to be included in the system boundaries of the ecological assessment. Therefore, the suppliers of the manufacturing equipment need to report their environmental data via the PEP, as shown in figure 1, which will later be used as input data for the ecological assessment of the observed manufacturing processes.

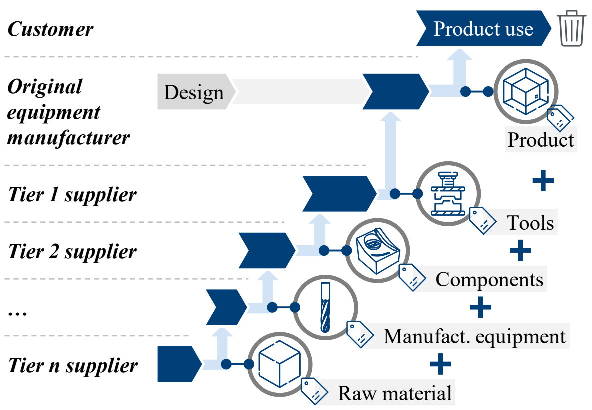

Fig. 1. Product environmental passport concept for value creation chain

One example is a milling tool, which is utilized by wear and tear in the technology application and thus causes environmental impacts in milling. This way, the environmental impact will increase for the observed product with each manufacturing step that is necessary for production.

A possibility to aggregate the recorded ecological data is the Digital Shadow, which is a digital copy of all acquired data of a product's manufacturing history. By development and implementation of technological models, the Digital Twin can be derived, which is a digital copy of a considered product, including condition assessment and prognosis of product characteristics, such as quality, productivity of the manufacturing processes, costs and additional: ecological assessment. [28] By extending the Digital Twin to include ecological aspects, manufacturing companies and SMEs in particular will be enabled to reach customer requirements [5, 29]. Likewise, this generates a contribution of the value creation chain to the increase of ecological sustainability, by increasing transparency and exploiting use-cause effects of environmental impacts.

As teased in chapter 1.3. it is crucial to integrate all life cycle stages in the ecological assessment to derive advantages or disadvantages of the manufacturing strategy in the use phase and end-of-life phase [17]. E.g., the application of coating to contour tool components leads to an increase in durability and will therefore increase the lifetime of the tool, which can result in an improved ecological assessment regarding the tool's life cycle. A comparison of single life cycle stages of technical products, such as the manufacturing phase, can mislead to false conclusions regarding a product's ecological assessment. Therefore, production companies must strive to develop ecological prognosis models for their manufactured goods. These models can be improved by systematically incorporating data from the use phase of customers and end users and by taking the end-of-life phase into account as early as the product design stage. When considering the life cycle of a tool, four different target dimensions can be determined for the individual life cycle phases in which the ecological data will be evaluated: "Manufacturing process", "Tool component", "Tool" and "Product". The target dimensions are discussed in detail in chapter 4. In order to be able to transfer from one target dimensions to the following one, the evaluation of the environmental impacts needs to be based on an evaluation system with a hierarchical structure so that it is possible to break down a tool's ecological evaluation down to its components and the associated process chains. In addition to the described framework of the target dimensions for ecological assessment in tooling, all other environmental impacts that have not been specifically assigned (e.g. induced by the energy consumption of the offices, the machine tool maintenance) must be summarized in the ecological overhead for a holistic approach. Ecological data can also be added here, which cannot be specifically assigned to the processes or the target dimensions due to their low data quality. The ecological overhead must be distributed over all products of a manufacturing company to be able to assign the environmental impacts to products.

3. Requirements of ecological assessment in tooling

To be able to implement the concept described in Chapter 2 in industry, framework conditions must be defined by value creation partners for the whole value creation chain. Uniform standards and methods are necessary for the detailed design of the ecological assessment [14]. When using (automated) LCA, one of the tasks for the value creation network is to clarify which impact assessment methods are to be used. The reason for this is that, depending on the impact assessment method used, the results of the environmental impacts can differ significantly for the same LCI. [30] Further, the value chain partners must agree on the environmental impacts to be reported. However, this is a minor problem, since the adjustment of the impact estimation methods in an automated LCA is possible, as explained in chapter 1.3. Yet exactly, a fully comprehensive data recording must be ensured so that with the applied LCA method both all processes and a complete LCI underlie the product assessment in the PEP. The applicability of such a solution can only be realized via a plug-and-play solution that automatically records and evaluates ecological data. Especially for SMEs, an automated approach is necessary, since otherwise the implementation of an LCA at the component level in tool manufacturing would lead to considerable effort due to the high process chain variance and is therefore not sensibly applicable. As a further framework condition in value creation chains, the reference value for offsetting across system boundaries of the target dimensions as well as life cycle phases must be taken into account. In LCA, the functional unit of the considered product system is used as the accounting value for environmental impacts. However, this must be defined at all assessment levels of the value chain. In this context, the required quality of a process result is to be regarded as a given framework condition, since a higher level of quality attainment in manufacturing is usually accompanied by a higher ecological effort. Through the life cycle oriented approach, however, the company's individual know-how in tool design and tool manufacturing can also be made visible at the ecological level, in that lower or higher environmental impacts result over the life cycle phases. Figure 2 shows an example of a process module for milling technology.

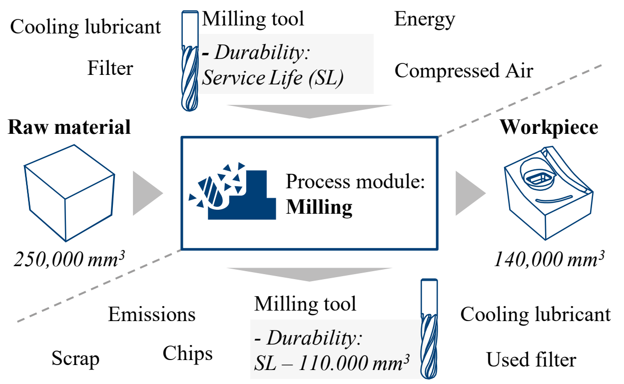

Fig. 2. System boundaries and functional unit of the milling technology

For the application of the functional unit of the exemplary product system, the service life data of milling tool manufacturers, for example, must be reconsidered, since time is not a meaningful reference value for an ecological evaluation. The reason for this is, among other things, the high variance of the process parameters and the associated deviating engagement conditions, for example in the comparison of rough milling and finishing. A better comparative value for the calculation of milling tool wear is, for example, the tool life volume.

4. Evaluation model for ecological assessment in tooling

This chapter describes the hierarchical evaluation model and explains the target dimensions in detail. The objective of the target dimensions is to combine the ecological assessment of the processes and life cycle phases. The life cycle of a tool is divided into three life cycle stages, to which the target dimensions are assigned, as illustrated in figure 3.

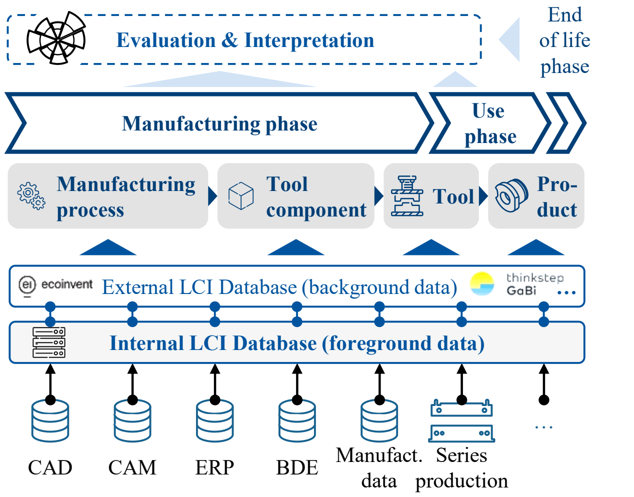

Fig. 3. Target dimensions across life cycle stages of a series production tool

The target dimension “Manufacturing process” for tool component production is divided into technology-specific process modules. Those are evaluated in the form of technology-specific description models for tool production. The description models must be filled with the LCI data and expanded to include further ecological efficiency indicators for process characterization and evaluation. These offer the possibility to perform a direct comparison of technologies and processes with the definition of the appropriate functional unit for manufacturing technologies, such as “removed material”, to identify environmental inefficiencies.

The dimension “Tool component” represents the sum of all manufacturing processes participating in the manufacturing of the component. It brings together the individual process assessments and maps the ecological assessment of the technology chain from raw material to finished component. By summing up the manufacturing processes, comparability can be achieved at the manufacturing level and the gradual summation of environmental impacts can be implemented at the component level. However, in industrial application in tooling, ecological comparability at the component level can only be applied to identical parts due to the unique manufacturing character. For example, ecological process chain comparisons can be carried out if, due to a production disruption or machine failure, a different production route is carried out for a tool component of identical construction.

The sum of all tool components, hence all assessments in the target dimension “Tool component”, results in the dimension “Tool”. The evaluation of the environmental impacts using LCA can thus be combined at the tool level and made available to the customer in the form of the PEP. In particular, at the tool level, efficiency indicators such as material efficiency or energy efficiency can be used for the internal improvement of the ecological efficiency of tool making. When compiling the environmental report for the PEP, it must be noted that the environmental data are only provided in aggregated form (at the tool level), since LCI data allow direct conclusions to be drawn about the manufacturing processes and technology chains used, which in turn represent the direct manufacturing technology knowhow of toolmaking. The disadvantage of such aggregated reporting is that the variable and subsequent calculation of new midpoint and endpoint impact categories using other impact assessment methods is hindered. A solution approach for this is a platform solution with specified and secured access rights for the primary data (LCI data) of the participating value creation partners.

The ecological consideration of the series process, which is realized with the tool, is considered in the target dimension "Product". Similar to the manufacturing processes, the evaluation is a process-oriented assessment that includes all mold-specific environmental impacts but also integrates ecological data from the production unit.

For the dimension "Product", description models as well as data acquisition methods for serial processes such as injection molding, sheet metal forming or solid forming have to be developed. Here, the material and energy flows of the mold in use and for the production of the final product must be taken into account [30]. This includes all spare parts over the intended life phase of the tool, but also, for example, waste produced such as sprues in injection molding or the punching grid in sheet metal forming. Figure 4 shows how the target dimensions are combined at the product level.

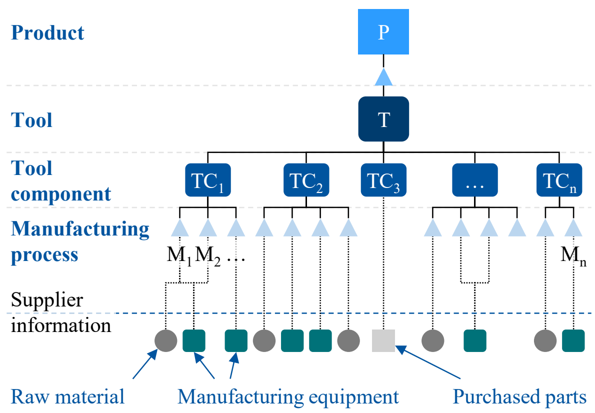

Fig. 4. Synthesis of the target dimensions

Finally, the "Company" dimension is used for the summarized ecological assessment of the resulting environmental impacts for all manufactured products. Based on the ecological data of the subordinate target dimensions, all processes and products can be aggregated at the company level to provide additional automated sustainability reporting for the ecological sustainability of the company. Furthermore, ecology overheads must be reported at the company level to ensure that the holistic approach is stringently implemented. The ecological overhead includes all environmental impacts that cannot be directly allocated to a value-adding activity and are therefore not shown as a manufacturing process in the valuation system. Furthermore, the environmental impacts of all non-assignable production resources, such as measuring equipment and other production aids, as well as, for example, the operation of a compressed air system, must also be included.

5. Validation and challenges

The implementation of the presented concept requires that the participating value creation partners expand the data acquisition in production and report their ecological data via a digital platform [5, 27]. This is the only way to ensure that the environmental impacts of products and manufacturing equipment can be aggregated across all value-adding partners in complex value creation networks and allocated to the finished product. The presented concept for life cycle oriented ecological assessment of tools has been validated in by the WZL of RWTH Aachen University, which has already tested and implemented automated data acquisition for productivity, quality and ecological data via the incubator technology chain. The applicability of the most challenging target dimension "Manufacturing Process" could be demonstrated in various trials on the manufacture of technical products. The methodology and the evaluation of ecological KPIs has been validated as published by Beckers and Grünert [31, 32]. In the industrial environment, initial trials were conducted with the WBA Aachener Werkzeugbauakademie, which is developing an Internet-of-Trusted-Things (IOTT) platform for connecting machine tools. This was extended to include ecological data and calculate an ecological PEP based on live production data. It was shown that the hierarchical structure of the target dimensions enables a tool evaluation based on process data from the tool's manufacturing process. Three key challenges were identified during the validation of the presented concept. When implementing the concept at the manufacturing process level, data acquisition is a major challenge for companies, especially SMEs. Due to the often low level of digitization, targeted data must be recorded at the manufacturing machines. Technology-specific description models including the associated data acquisition methods must be developed and made available to the tooling industry. Another challenge for ecological assessment in practice is the evaluation of LCI data. Secondary data in the form of environmental databases are needed to convert these into environmental impacts. For manufacturing technologies, however, there is a lack of databases that enable an accurate ecological evaluation. Existing databases, such as Ecoinvent, Probas or the Gabi database, contain only a small number of manufacturing technology data records, which in turn consist in part of outdated data. The third challenge is the fact that very few value creation partners are not yet in a position to assess and report their environmental impacts due to the challenges listed above. Furthermore, a lack of standards for the type of reporting is an obstacle for many companies. Here, a uniform system must be established in which technological pioneers start to report ecological data of their produced products so that progressively the further value creation partners can work on the reporting of their own environmental impacts.

6. Conclusion and outlook

This paper presented a concept and scientific approach to ecologically evaluate technical products, such as tools by using LCA and aggregate the assessment across complex value chains. The framework of an ecological assessment across life cycle stages has been presented, including the evaluation method, target dimensions and the hierarchical structure of the evaluation method. Furthermore, requirements and challenges have been discussed and the need for further research has been pointed out. In addition to tools, the overall concept for life-cycle-oriented ecological assessment can also be applied to other technical products, taking into account the presented boundary conditions in chapter 3. Furthermore, it was emphasized that platforms for the reporting of environmental data are indispensable for the consolidation of data, e.g. the product ecological passport.

In the outlook, the applicability of the presented concept is still slowed down due to the lack of manufacturing databases for ecological data. There is also a need for further research in the evaluation of data quality for LCA to further specify the requirements for an ecological assessment. Further development is needed in the implementation of a plug-and-play LCA to enable SMEs to report environmental impacts. Likewise, the environmental overhead needs to be further specified and criteria and methodologies are needed to allocate the environmental overheads to the value-adding processes. Finally, for the presented concept in tooling, the end-of-life phase of tools has to be investigated and detailed to be able to map the complete life cycle of a tool. By investigating the different technologies for recycling or disposal at the end-of-life, circular economy potentials can be identified to further increase the sustainability of tools.

References

[1] Abubakr, M., Abbas, A.T., Tomaz, I., Soliman, M.S. et al., 2020. Sustainable and Smart Manufacturing: An Integrated Approach 12, p. 2280.
[2] Birkie, S.E., 2018. Exploring business model innovation for sustainable production: lessons from Swedish manufacturers 25, p. 247.
[3] Metsola, R., Bek, M., 2022. DIRECTIVE (EU) 2022/2464 OF THE EUROPEAN PARLIAMENT AND OF THE COUNCIL, in Official Journal of the European Union.
[4] Kaplan, R.S., Ramanna, K., 2021. How to Fix ESG Reporting.
[5] Glatt, M., Kölsch, P., Siedler, C., Langlotz, P. et al., 2021. Edge-based Digital Twin to trace and ensure sustainability in cross-company production networks 98, p. 276.
[6] Sfez, S., Dewulf, J., Soete, W. de, Schaubroeck, T. et al., 2017. Toward a Framework for Resource Efficiency Evaluation in Industry: Recommendations for Research and Innovation Projects 6, p. 5.
[7] Swarnakar, V., Singh, A.R., Antony, J., Tiwari, A.K. et al., 2021. Development of a conceptual method for sustainability assessment in manufacturing 158, p. 107403.
[8] Cai, W., Lai, K., 2021. Sustainability assessment of mechanical manufacturing systems in the industrial sector 135, p. 110169.
[9] Kaldas, O., Shihata, L.A., Kiefer, J., 2021. An index-based sustainability assessment framework for manufacturing organizations 97, p. 235.
[10] Kumar, M., Mani, M., 2021. Towards an interdisciplinary framework for effective sustainability assessment in manufacturing 98, p. 79.
[11] Saad, M.H., Nazzal, M.A., Darras, B.M., 2019. A general framework for sustainability assessment of manufacturing processes 97, p. 211.
[12] Dickinson, P. Carbon Disclosure Project - Guidance for companies. https://www.cdp.net/en/guidance/guidance-for-companies. Accessed 13.02.23.
[13] Kaplan, R.S., Ramanna, K., 1 November 2021. Accounting for Climate Change. https://hbr.org/2021/11/accounting-for-climate-change. Accessed 29 January 2023.
[14] Schramm, A., Richter, F., Götze, U., 2020. Life Cycle Sustainability Assessment for manufacturing – analysis of existing approaches 43, p. 712.
[15] Vollmer, T., Schmitt, R., 2015. Integrated shop floor data management for increasing energy and resource efficiency in manufacturing.
[16] Grünebaum, T., Hermann, L., Trauth, D., Bergs, T., 2019. Towards sustainable production: a methodology to assess influences between life cycle phases in tool manufacturing 80, p. 376.
[17] Grünebaum, T., Müller, U., Rey, J., Barth, S. et al., 2019. Life cycle oriented technology chain optimization: a methodology to identify the influences of tool manufacturing on environmental impacts caused in the tool's use phase 13, p. 567.
[18] Boos, W., Lukas, G., Ochel, T., Haase, B., Trisjono, J., Calchera, R., 2022. Der Werkzeugbau als Gesamtlösungsanbieter. WBA Aachener Werkzeugbau Akademie GmbH, Aachen.
[19] Boos, W., Kelzenberg, C., Prümmer, M., Goertz, D., Boshof, J., Horstkotte, R., Ochel, T., Lürken, C., 2022. Tooling in Germany. WBA Aachener Werkzeugbau Akademie GmbH, Aachen.
[20] Boos, W., Lukas, G., Kessler, N., Schweins, J., Haase, B., Kenfenheuer, J., 2022. World of Tooling 2022. WBA Aachener Werkzeugbau Akademie GmbH, Aachen.
[21] Boos, W., Kelzenberg, C., Wiese, J., Boshof, J., Kessler, N., Haase, B., 2022. IT-Infrastruktur zur digitalen Vernetzung: Im Werkzeugbau. WBA Aachener Werkzeugbau Akademie GmbH, Aachen.
[22] Boos, W., Kelzenberg, C., Helbig, J., Busch, M., Graberg, T., Schweins, J., 2022. Wettbewerbsfaktor Nachhaltigkeit: Ein Differenzierungsmerkmal für den Werkzeugbau. WBA Aachener Werkzeugbau Akademie GmbH, Aachen.
[23] Koffler, C., Krinke, S., Schebek, L., Buchgeister, J., 2008. Volkswagen slimLCI: a procedure for streamlined inventory modelling within life cycle assessment of vehicles 46, p. 172.
[24] Huijbregts, M.A.J., Steinmann, Z.J.N., Elshout, P.M.F., Stam, G. et al., 2017. ReCiPe2016: a harmonised life cycle impact assessment method at midpoint and endpoint level 22, p. 138.
[25] Castellani, V., Benini, L., Sala, S., Pant, R., 2016. A distance-to-target weighting method for Europe 2020 21, p. 1159.
[26] Jungbluth, N., Büsser, S., Frischknecht, R., Flury, K. et al., 2012. Feasibility of environmental product information based on life cycle thinking and recommendations for Switzerland 28, p. 187.
[27] Franciosi, C., Miranda, S., Veneroso, C.R., Riemma, S., 2022. Improving industrial sustainability by the use of digital twin models in maintenance and production activities 55, p. 37.
[28] Bergs, T., Gierlings, S., Auerbach, T., Klink, A. et al., 2021. The Concept of Digital Twin and Digital Shadow in Manufacturing 101, p. 81.
[29] Stock, T., Seliger, G., 2016. Opportunities of Sustainable Manufacturing in Industry 4.0 40, p. 536.
[30] Elduque, A., Javierre, C., Elduque, D., Fernández, Á., 2015. LCI Databases Sensitivity Analysis of the Environmental Impact of the Injection Molding Process 7, p. 3792.
[31] Beckers, A., Hommen, T., Becker, M., Kornely, M.J. et al., 2022. Digitalized manufacturing process sequences – foundations and analysis of the economic and ecological potential 39, p. 387.
[32] Grünert, G., Grünebaum, T., Beckers, A., Stauder, L. et al., 2023. Methodology for the selection of manufacturing technology chains based on ecologic and economic performance indicators 66, p. 42.