Available online at www.sciencedirect.com

ScienceDirect

Procedia CIRP 116 (2023) 47–52

www.elsevier.com/locate/procedia

30th CIRP Life Cycle Engineering Conference.

A Methodology for Sustainability Assessment and Decision Support for Sustainable Handling Systems

Johannes Scholz*[a], Luca Johannes Dilger[a], Marco Friedmann[a], Jürgen Fleischer[a]

[a]*wbk Institute of Production Science, Karlsruhe Institute of Technology, Kaiserstraße 12, 76131 Karlsruhe*
* Corresponding author. Tel.: +49 1525 4375433; *E-mail address:* johannes.scholz@kit.edu

Abstract

Sustainable manufacturing is an important goal to reduce the carbon footprint and securing the economic success of companies. To reach sustainable manufacturing it is also necessary to use sustainable equipment. For this purpose, the sustainability indicators of the asset during its whole life cycle need to be considered for decision making during the design and selection of equipment. Missing analysis methods as well as missing awareness of the importance are obstacles in decision making. Therefore, a multi-criterial analysis method for handling systems for decision empowerment is presented in this paper. The presented methodology enables the engineer to analyze the suppliers for decision making in the purchasing process as well as the identification of weak points regarding sustainability in the handling systems. The methodology offers the possibility of analyzing a system of several parts as a whole, rather than just individual parts. The methodology is implemented in a usable software prototype which has a graphical interface for the data input and can be connected to conventional databases. The usability of the tool is shown with a handling system consisting of an industrial robot and a gripping system.

Keywords: Sustainability, Multi-criterial decision making, Model-based Systems Engineering

1. Introduction

Through increasing energy costs, high cost pressure on companies, legal regulations and an increasing focus of customers on sustainable products the importance of sustainable manufacturing is increasing. For companies draw up their ecological balance sheet in accordance with the Greenhouse Gas Protocol, emissions caused during production are relevant, as are emissions caused during the manufacture of equipment. [1]

As a result, suppliers of operating equipment for automated production plants are under pressure to develop ecological optimized equipment and systems with acceptable costs. A part of nearly every automated production system are handling systems, which consist of a handling device, for example a robot, a gripper and periphery. [2, 3]The components are often manufactured in series by robot manufacturers or gripper manufacturers and combined by a system integrator with high cost and time pressure. Due to this, the engineer of a system integrator is focusing on the functionality of the system and low investment costs. Ecological aspects normally are falling short in the evaluation of systems. In order to support system integrators in this area of conflict, the paper presents a methodology for sustainability assessment across life phases. This should facilitate the appropriate modelling of the entire system as well as the inclusion of external and internal components.

The paper is structured in five parts. In section 2 the understanding of sustainability as well as existing approaches for sustainability assessment are presented. Furthermore, a development approach based on model-based systems engineering (MBSE) to increase sustainability with lightweight design is presented. Based on the identified research gap the developed methodology is presented in section 3 and the implementation in Section 4. The paper is closed with a conclusion and an outlook on future work.

10.1016/j.procir.2023.02.009

2. Related Work

Sustainability, in its broadest sense, is "the long-term safeguarding and further development of the foundations of human civilization in the face of the limited resilience of the natural environment and economic and social risks to the future." [4] Garetti and Taisch [5] described sustainable manufacturing as the ability to smartly use natural resources. They also mention that sustainable solutions are required.

But contributing to corporate sustainability requires a long-term strategy with short-term actions. Furthermore, sustainabile manufacturing is more than just the ecological point of view. [6] Stark et al. [7] define sustainable manufacturing as “creation of discrete manufactured products that in fulfilling their functionality over their entire life cycle cause a manageable amount of impacts on the environment (nature and society) while delivering economic and societal value”. This definition shows the area of conflict between a lowinvestment costs and and highly energy efficient production equipment. Additionally, the diferent aspects need to be evaluated.

To meet the challenge of the different aspects, the triple-bottom-line approach (TBL) is often used to reduce the complexity. The approach divides sustainability into the three pillars economic, ecological and social sphere with similar importance. [8] The economic sphere addresses the long-term preservation of economic success. For handling systems, low investment costs, low energy costs during operation and low maintenance costs are worth mentioning. The long-term preservation of the environment and its impact is addressed with the ecological sphere which addresses small emissions during raw material extraction, high recycling rates of the equipment and long lifetime of the components.

With the social sphere the interaction between human and products is described. [8] In more recent approaches, the ecological dimension is even seen as a framework for the social and economic dimension since the environmental impact is of increasing interest. [9] This paper focuses on the ecological and economic sphere.

Eslami et al. [10] and Ahmad et al. [11] clearly emphasise the importance of sustainable manufacturing and sustainability assessment in their reviews. It becomes clear that different approaches exist with different goals and possibilities of influence. The description of sustainability is based on the TBL.

Guo et al. [12] describes a systematic hierarchy of green supplier evaluation criteria for sustainable supplier selection in the field of apparel manufacturing. For the analysis of the supplier an expert is needed because the subjective opinion has high impact on the decision.

The approach integrates quantitative criteria like costs and lead time as well as the maturity of the technology and the supplier’s environmental competency, which can only be described qualitatively. To overcome the challenge comparing quantitative and qualitative values fuzzy-logic is used. In contrast to classical set theory, fuzzy logic allows values to belong partially to a set. [13] Hashemi et al. [14] presents an approach to reduce the impact of subjective expert opinions, by smoothing the uncertainties.

To sum up, these approaches support the selection of suppliers for a selected component of a product. However, the approaches do not consider the impact of decisions on the whole system. Additionally, they do not support optimizing the component to improve sustainability.

Product specific life cycle assessment approaches are used to compare sustainable product alternatives. A guideline for these approaches is the DIN EN ISO 14044 [15], which describes the procedure for a life-cycle assessment. However, it is just focused on the ecological aspect of sustainability. Economic aspects are not considered. The methodology from Zhang and Cai [16] the “overall life cycle comprehensive assessment method” (OLCCA) supports analyzing pneumatic and electrical actuators regarding technical, economic and ecological aspects. For this purpose, the actuators are described by several models to analyze the energy consumption during usage and environmental and economic impacts in other phases. He et al. [17] and Hemdi et al. [18]and defines a product sustainability indicator as measurement for product sustainability. The indicator is calculated based on hierarchical structured evaluation categories. The used indicators are calculated based on an Analytic Hierarchy Process (AHP). AHP is a method to solve complex decision problems and it can handle target conflicts with a high amount of criteria. One decision variable is defined and divided top-down in criteria with impact on the decision.

The third group of approaches deals with the analysis of manufacturing processes. These approaches are focused on specific manufacturing processes like 3D printing. [19] Other approaches are focused on sustainability optimization of whole production systems from a planning point of view. [20]

It can be summarized that methodologies based on multi-criteria decision making (MCDM) are an established technique for determining sustainability indicators for processes, products and suppliers. The presented approaches are not able to cover the whole lifecycle as well as handling the challenges through the high amount of standardized components and the complexity of handling systems. Ahmad et al. [11] point out that fuzzy approaches offer potential for dealing with uncertainties and that these are already being used, but that there is a need for further research.

To select and design sustainable handling systems over all life-stages an approach is required which is able to handle uncertainties, weighting the life-stages against each other and model the system. A measurement for increasing sustainability of handling systems could be lightweight design. Therefore, Scholz et al. [21] and Kaspar et al. [22] present a systematic approach based on MBSE to develop lightweight products in a systematic way and focused on reducing CO2 emissions with accetable cost. Starting with the Requirements Engineering (R), the functional design (F), the logical architecture (L), technical design (T) and physical design (P). the approach is taking into account manufacturing and usage.But the approach lacks a consistent evaluation methodology and the consideration of other sustainability criteria.

3. Methodology

The presented approach proposes a methodology for the economic-ecological sustainability assessment and decision empowerment of handling system in the context of MBSE. The advantages are an easy understanding of the results and the support of decision making based on sustainability criteria during design.

The decision problem is structured with an AHP in several indicators. The main criteria for the decision is the sustainability score. Based on the TBL and the focus of the approach the sustainability score is subdivided in two indices, the economic index and the environmental index. The whole structure of the AHP tree is shown in Fig. 1. The indicator structure is built up based on Hemdi et al. [18] extended by the environmental-competency indicator to evaluate suppliers which provide less data, the material index to evaluate the type of used material and the energy indicator measuring the energy consumption. Through the AHP it is possible to weight the indicators or indices against each other.

Additionally, a second hierarchical indicator tree is built up to describe the Life-Cycle-Sustainability-Index. It consists of indicators for the life-phases manufacturing, usage and end-of-life. Furthermore, the manufacturing phase is separated in an internal indicator and an external indicator. Through the second tree structure weak points of the system can be brought into a temporal context over the life cycle. Although the two scores were calculated on the basis of the same values, the values are different. The reason for this is a different assignment of the underlying values to the categories. Therefore, it is recommended to use the sustainable score for decisions between different solutions and the life-cycle sustainability index for identifying optimization potentials in the system.

Compared to existing approaches this second indicator tree increases the transparency and can better support in selection problems.

The indicators of the sustainability score as well as the indicators of the life-cycle sustainability index are calculated with 30 sustainability categories. These sustainable categories describe the life-cycle of the evaluated production equipment. The categories are quantitative or qualitative values and calculated with the later explained modeling of the system. Thus, the properties and manufacturing processes of a component and the impacts of manufacturing processes are summed up to a standardized ratio system.

In order to calculate the indicators based on the categories, they are assigned to the indicators using weightings. Here it is possible to assign the categories partly to more than one indicator. The weighting of the categories, indices and indicators regarding their bottom-up impact is done with a pairwise comparison.

The categories address the waste, mass utilisation, CO2-emissions and CO2-equivalent emissions, energy consumption and energy type, costs and status of technology. To consider the internally produced components as well as purchased components the categories differentiate between internal, supplier and transport. Furthermore there are categories for the material, the end-of-life waste and the environmental-mangement-system of the supplier.

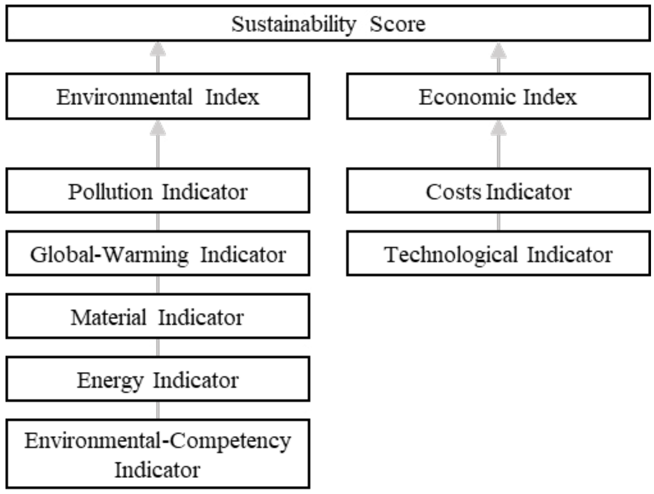

Fig. 1: Criteria tree of the Analytic Hierarchy Process

The described indicator structure is integrated in a procedure for modeling and calculation of the sustainability score which is shown in Fig. 2. The user selects system components and models them with properties and processes, which are the basis for the calculations. As output the user gets visualized optimization potentials based on the categories, indices indicators and scores.

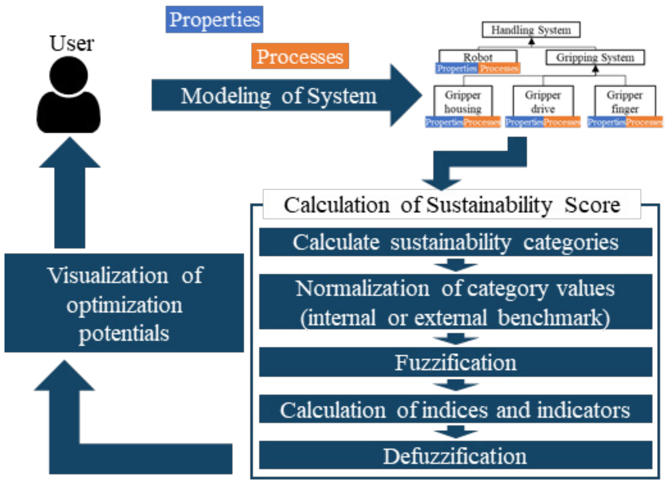

Fig. 2: Structure of the methodology

The system is modelled with the approach from Scholz et al. [21]and Kaspar et al. [22]. Requirements of the system could be the weight of handling object, required accelerations and environmental requirements. Afterwards, the system is described by the required functions like handling an object. The functions are structured hierarchical starting with the main task of the system. This can be further detailed through subdividing the functions. Defining logical elements which fulfils the functions in parallel, these are also structured in a hierarchical tree. The technical solutions are assigned to the logical elements. This leads to a tree G (K, E), which is used in the presented approach as basis for modeling. This enables a bottom-up filling of component properties. The leaves K of the tree represent the individual parts of the system, E represents the edges between the leaves. In Fig. 3 a handling system is modelled and it consists of a robot and a gripping system, which is subdivided into gripper housing, gripper drive and gripper finger. If a leaf of the tree has no children, it is described by the properties in Table 1. As the unit column shows the properties are quantitative values besides the material. In Fig. 3 the components in level 3 and the robot in level 2 are described with the properties, because they are the smallest functional unit in the system, which is purchased or manufactured by the system integrator. Furthermore, the components are described with processes. Based on the literature the processes are mainly described by an input-output analysis supplemented by quality and cost factors. [23] Also, the supplier's environmental protection activity can be described if the component would be purchased. In the case of processes, a distinction is made between manufacturing processes and transport. Transport is relevant if the component is purchased. Since, there is often a lack of precise data on the processes involved in purchased components, these can also be assessed qualitatively. With the structured description of the components and the assignment of the processes a holistic view of the system can be modelled.

The properties in Table 1 and the processes can directly be improved by measurements on the components.

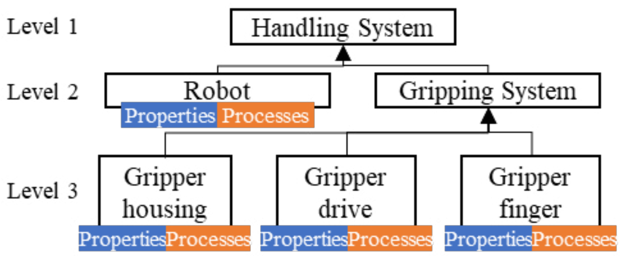

Fig. 3: Example of the tree structure

Table 1. Component properties for sustainability analysis

Properties	Description	Unit
Material	Type of material	-
Material cost	Costs for the material	€
Life expectancy	Expected lifetime of the component	years
Energy consumption	Expected energy consumption of the component during the use phase	Wh
Recycling rate	Percentage of the component which can be used after the recycling process for a new product	%
Recycling cost	Expected recycling and disposal cost	€
Recycling energy	Needed energy for recycling processes	Wh

With the modeled components as a basis, the 30 sustainability categories are calculated as first step for calculating the sustainability score and the life-cycle sustainability index.

Since, only the components without child components are described with properties and processes, bottom-up calculation of the categories in the component tree is carried out. In the example of Fig. 3 the category values for the gripping system are calculated based on the category values of the components in level 3. Quantitative values are added and qualitative values are averaged for the gripping system.

For calculating the indicators based on the category values uncertainties in data, quantitative values with different units and qualitative values need to be handled. Therefore, following Hemdi et al. [18] a fuzzy inference system is used.

The first step of a fuzzy inference system is fuzzification. The input values need to be assigned to the fuzzy-sets. For this purpose, membership functions and characteristic digits of the fuzzy sets have to be defined. Due to the data model with 30 sustainability categories with different units 30 membership functions and characteristic digits would be necessary. This can be simplified by normalizing the categories, but a benchmark is required. The normalization process can be separated into two cases. In the first case the category values are normalized based on the maximum values in the system for each category. Because of the bottom-up calculation of the categories these are always the category values of the parent component in the level above. In Fig. 3 the category values of the handling system, would be the benchmark for the components in level 2. The benchmark for the level 3 components connected to the gripping system is the gripping system. This procedure is particularly suitable for comparing different solutions within a development process. In the second case an external benchmark is used. For example, the categories are calculated for a handling system on the market with the same requirements and functions and it can be analyzed if the developed product is better than the existing one. For comparing different systems the usage of the same benchmark is important.

For both cases, it is the same calculation procedure of the normalized values. First, the values of the children are normalized by the values of the parent component and a discount factor d_k. The discount factor d_k is obtained for each category by the quotient of the maximum value of the product (top parent component) and the initial threshold values b_k. If an internal benchmark is used, the discount factor $d_k = 1$ for each category.

Equation (1) represents the normalization of the category values of a component. For the top component is $c_{ki} = b_k$. By the edge set E, each parent-child relation is defined by an edge e{i,j}.

$$c_{kj,normalized} = \frac{c_{kj}}{c_{ki} \cdot d_k} \quad (1)$$

c_{kj} = sustainability category value of component (j) and category (k)

c_{ki} = sustainability category value of component (i) and category (k)

Each category value of the subordinate component can be evaluated based on the category value of the parent component with this formula. Furthermore, the discount factor d_k creates the possibility that the ratio of the category values between the components on one level remains the same, no matter which b_k is chosen. This leads to a consistent evaluation and every normalized value is within the interval $[0, 1 \cdot d_k]$. In the special case $b_k = 0$ equation (1) is invalid, so the category value $c_{kj,normalized}$ is defined as 0 in this case.

Defining the membership functions of the fuzzy-sets based on the normalized category values allows the usage of the same fuzzy sets and membership functions for all categories.

The impact of the categories towards sustainability is assigned to the linguistic variables (low, medium, high). For each linguistic variable a membership function is created which describes the fuzzy-set (low, medium, high). The approach uses trapezoidal membership functions because this way all three fuzzy sets take the same importance. (Fig. 5) Through the fuzzification the imprecision in the available data is less significant in the further course of the calculation, because each category value is assigned a partial affiliation $\mu_{low}(x), \mu_{medium}(x), \mu_{high}(x)$ to the fuzzy-set (low, medium, high).

In the next step, based on the membership values of the categories, the overlying indicators, indices and the sustainability score from Fig. 2 are calculated. For this purpose, the values $\mu_{low}(x), \mu_{medium}(x), \mu_{high}(x)$ of the categories belonging to an indicator are added up together with in the pairwise comparison determined weights of the categories. The indicator is then described by weighted average of the values of the categories.

The next step is the inference of the fuzzy values. The if-then rules are defined according to Mamdani. Thereby, the affiliation to a linguistic variable implies the assignment on a fuzzy set, as it is described via triangular functions. The application of the rules results in a new fuzzy-set. The new fuzzy set is defuzzied to a value (score) using the Center-Of-Gravity method. The defuzzification thus turns the fuzzy set into a usable score within the interval between 0 and 1. [24]

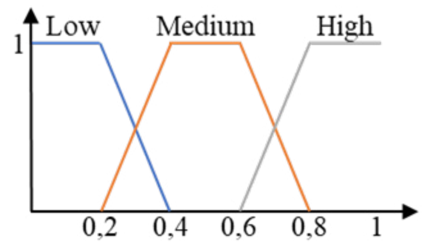

Fig. 4: Fuzzy sets of the linguistic variables LOW, MEDIUM, HIGH

After calculating the indices, indicators and the sustainability score the evaluation of the result is carried out in two separate approaches. In order to identify weak points with a negative sustainability influence in the system, the sustainability score of each component is weighted in terms of its influence on functional performance and the highest value is identified. This component is considered to be the weak point of the entire system and is the component where changes can be made most effectively. Afterwards, the evaluation criteria are searched top-down for the indicators and indices with the worst values. Based on these indications, targeted measures for improvement can be sought. For example, another component can be chosen or the material is changed. The effects are shown in the change of the indicators, indices and the sustainability score. Since the categories are interrelated, this does not ensure that an improvement in the overall system will actually occur. To provide greater certainty, possible positive or negative influences of other categories are added to the result with a correlation matrix.

For decision making all components and their indices are listed. In addition to that these values can serve as a benchmark for new developments and improved processes. Furthermore, this evaluation offers a possibility to document the results. If two analyses are performed on the basis of the same maximum values (benchmark), the changes in the index values can be quantified, for example as a percentage, so that all the bases for a benchmarking process are fulfilled. Through the life-cycle sustainability index weaknesses in life-cycle phases can be identified and addressed in the development.

4. Software Prototype

The methodology was implemented with Python 3.9* in a software prototype to demonstrate functionality and the possibility to integrate it in a digital toolchain. For this purpose, the application implemented in a modularly structure. First of all, the prototype asks the user for the system structure and it can be build up regarding Fig. 3. Afterwards each smallest functional unit of the tree can be described in a Graphical User Interface with the properties from Table 1 and the processes. To reduce the effort for data integration the tool can be connected to databases like GRANTA Edupack [25]. Thus, required information regarding material can be automatically integratd in the description model.

For comparing different solutions external benchmarks can be used. For integration of external benchmark a CSV-File is used, which can be imported to the software prototype. The CSV-File contains a maximum value for each category. If an internal benchmark is used this CSV-File is generated by the software and can be stored for new solutions later. In particular, an internally generated benchmark can also be given to suppliers, who can use this file to evaluate their product, so that suppliers can be compared on the basis of the same benchmark values. This can help to eliminate data confidentiality concerns, as only the classification against the competition is transferred.

The assignment and weighting of the categories to the indices and indicators for the AHP is pre-implemented. The prototype calculates the categories, indices and indicators based on the described methodology.

The output of the software implementation is a textual description of the worst categories, indices and indicators in the system as well as the components and the overall sustainability score. For comparison of different solutions the result can be stored and changes can be made.

As described in the methodology chapter it is possible to identify bad categories or indices of components. For this purpose, the indices are presented in a component-indicator-matrix (Fig. 5). The components are in the rows and the indices in the columns. The rating of the index is visualized by the color scheme. The darker the red in the matrix field, the worse the rating. This type of visualization provides a quick overview and good comparability, since all important indices, as well as all components can be seen in one view. In the example in Fig. 5 the sustainability score of the gripping system is 0.7. The worst indicator is the economic indicator. If the component tree is searched top-down, it can be seen that the economic factor of the gripper is worse than that of the robot. This gives a

* https://www.python.org/downloads/release/python-390/

starting point for optimization. Afterwards, the categories are checked and the affecting properties are identified. Based on the identified properties optimization measurements can be identified. Through the indicator structure the effect of measurements like lightweight design can be measured on the whole system as well as for the specific component.

The software prototype was tested with a case study using a handling system consisting of a robot and a gripping system with 25 parts. Due to poor data, some assumptions needed to be made, but the evaluation methodology was shown to be sensitive to change and suitable for comparison.

	Envir. indicator	Economic indicator	Sustainabilty Score
Gripping system	0.6357	0.8849	0.701
Gripper housing	0.2692	0.1085	0.2857
Gripper drive	0.387	0.3938	0.4

Fig. 5: Excerpt of the Component-indices-matrix as heatmap for system evaluation

5. Conclusion and Future Work

The methodology provides an approach to evaluate products from a sustainability perspective. Through the standardized description of components and the focus on handling uncertainties the methodology meets the requirements of system integrators for handling systems.

The different life stages and the economic and ecologic factors are summarized in a developed sustainability score as well as in a life-cycle sustainability index. The sustainability score, the indicators and indices are calculated based on categories with the AHP. To overcome the challenge of uncertainties and qualitative and quantitative data it is combined with fuzzy-logic.

The used AHP neglected interdependencies between the sustainability categories. This issue can be solved with using an Analytic Network Process which has the possibility to integrate interdependencies in the decision process. The evaluation approach gives the opportunity to apply targeted measures to improve the sustainability.

Currently, many of the properties of the components need to be inserted manually. Connecting the methodology in a digital toolchain with the right software tools and models to provide the needed information for selected categories will reduce the effort of analyzing. For example, describing the handling system in a mechatronic simulation the energy consumption can be calculated automatically. To improve the comparison of different solutions an industry specific benchmark is needed.

Furthermore, technical parameters like accuracy parameters need to be integrated.

Acknowledgments

The authors thank the “Technologietransfer-Programm Leichtbau (TTP LB)” of the Federal Ministry for Economic Affairs and Climate Action (BMWK) for supporting their research within their project “SyProLei” (03LB2007G)

References

[1] Bhatia P., Cummis C., Draucker L., Rich D., Lahd H. and Brown A. Greenhouse gas protocol product life cycle accounting and reporting standard.
[2] Schmalz J. and Reinhart G., 2014. Automated Selection and Dimensioning of Gripper Systems, Procedia CIRP 23, 212–216.
[3] Friedmann M. and Fleischer J., 2022. Automated Configuration of Modular Gripper Fingers, Procedia CIRP 106, 70–75.
[4] Grunwald A. and Kopfmüller J., Nachhaltigkeit, 2nd ed. Frankfurt am Main: Campus Frankfurt/New York, 2012.
[5] Garetti M. and Taisch M., 2012. Sustainable manufacturing: trends and research challenges, Production Planning & Control 23, 83–104.
[6] Moldavska A. and Welo T., 2017. The concept of sustainable manufacturing and its definitions: A content-analysis based literature review, Journal of Cleaner Production 166, 744–755.
[7] Stark R., Seliger G. and Bonvoisin J., Sustainable Manufacturing. Cham: Springer International Publishing, 2017.
[8] Pope J., Annandale D. and Morrison-Saunders A., 2004. Conceptualising sustainability assessment, Environmental Impact Assessment Review 24, 595–616.
[9] Hauschild M. Z., Herrmann C. and Kara S., 2017. An Integrated Framework for Life Cycle Engineering, Procedia CIRP 61, 2–9.
[10] Eslami Y., Lezoche M., Panetto H. and Dassisti M., 2021. On analysing sustainability assessment in manufacturing organisations: a survey, International Journal of Production Research 59, 4108–4139.
[11] Ahmad S., Wong K. Y. and Butt S. I., 2022. Status of sustainable manufacturing practices: literature review and trends of triple bottom-line-based sustainability assessment methodologies, Environmental science and pollution research international.
[12] Guo Z., Liu H., Zhang D. and Yang J., 2017. Green Supplier Evaluation and Selection in Apparel Manufacturing Using a Fuzzy Multi-Criteria Decision-Making Approach, Sustainability 9, 1–13.
[13] Zadeh L. A., 1988. Fuzzy logic, Computer 21, 83–93.
[14] Hashemi S. H., Karimi A. and Tavana M., 2015. An integrated green supplier selection approach with analytic network process and improved Grey relational analysis, International Journal of Production Economics 159, 178–191.
[15] DIN 14044: Environmental management – Life cycle assessment – Requirements and guidelines, 14044.
[16] Zhang Y. and Cai M., 2014. Overall life cycle comprehensive assessment of pneumatic and electric actuator, Chin. J. Mech. Eng. 27, 584–594.
[17] He B., Luo T. and Huang S., 2019. Product sustainability assessment for product life cycle, Journal of Cleaner Production 206, 238–250.
[18] Hemdi A. R., Saman M. Z. M. and Sharif S., 2013. Sustainability evaluation using fuzzy inference methods, International Journal of Sustainable Energy 32, 169–185.
[19] Yosofi M., Kerbrat O. and Mognol P., 2018. Framework to Combine Technical, Economic and Environmental Points of View of Additive Manufacturing Processes, Procedia CIRP 69, 118–123.
[20] Blume S. A., Resource Efficiency in Manufacturing Value Chains. Cham: Springer International Publishing, 2020.
[21] Scholz J. et al., 2021. Concept of a Systemic Development Process to Realize Lightweight Potentials, Zeitschrift für wirtschaftlichen Fabrikbetrieb 116, 797–800.
[22] Kaspar J. et al., 2022. SyProLei - A systematic product development process to exploit lightweight potentials while considering costs and CO2 emissions, Procedia CIRP 109, 520–525.
[23] Mani M., Madan J., Lee J. H., Lyons K. W. and Gupta S. K., 2014. Sustainability characterisation for manufacturing processes, International Journal of Production Research 52, 5895–5912.
[24] Hudec M., Fuzziness in Information Systems: How to Deal with Crisp and Fuzzy Data in Selection, Classification, and Summarization, 1st ed. Cham: Springer International Publishing; Imprint: Springer, 2016.
[25] Ansys Granta, Granta EduPack. [Online]. Verfügbar: https://www.grantadesign.com/de/education/ces-edupack/ (accessed: Sep. 6 2022).