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Sustainability Indicators for Discrete Manufacturing Processes Applied to Grinding Technology

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ABSTRACT
As environmental and social awareness in production engineering rises, sustainability in discrete manufacturing processes has to be controlled better and enhanced. Sustainability indicators offer a simple and affordable solution for quickly assessing sustainability; however, they have been employed rarely on the process level. This study selects simple and relevant sustainability indicators and discusses different means of normalization. The sustainability indicators can be displayed as a performance profile, which is individual to each manufacturing process variant. In addition, the indicators can be simplified to one sustainability indicator through a utility analysis allowing for a quick comparison between different process variants. The whole procedure is executed with a grinding process case study. This work provides a straightforward method for evaluating sustainability of discrete manufacturing processes.

KEYWORDS
Grinding, sustainable manufacturing, sustainability indicators

INTRODUCTION

Manufacturing has a large impact on worldwide energy use and resource consumption. Discrete manufacturing processes consume energy and resources as they transform raw material into final products. Traditionally, research on manufacturing processes was mainly conducted to improve efficiency and accuracy and to lower cost. With increasing awareness, the control and reduction of environmental and social impacts of manufacturing processes become an additional objective [1, 2].

Sustainability encompasses the three pillars of economic, environmental and social sustainability [3]. Companies have to find ways to capture and measure their sustainability performance. The most commonly used method is Life Cycle Assessment (LCA), focusing on environmental sustainability. One problem in using LCA, however, is the need for specific databases and quantitative data, sometimes in great detail. In addition, the analysis often focuses on high level endpoints of the environmental impact (e.g., ocean depletion, human health) rather than on midpoints (e.g., energy use, green house gas emission).

Another method is the use of “Sustainability Indicators” (SI). An indicator may be defined “as a measure or an aggregation of measures from which conclusions on the phenomenon of interest can be inferred” [4]. Sustainability indicators can capture all three dimensions of sustainability and help with the evaluation on many levels (companies, facilities, processes, and products). Especially for users with limited means and resources, SIs provide a good method for analyzing sustainability. Companies can assess their actual situation with the indicators, raise their awareness and set their goals [3].

In the last years, different approaches to measure sustainability performance have arisen [4, 5, 6]. However, it can be difficult to apply those to particular companies, processes, or products and companies are challenged to decide on appropriate and useful indicators [4]. In order to avoid an additional burden, the methods must be preferably simple and affordable to apply, have low assessment time, and should not rely on user experience.

In addition, the practical application of sustainability indicators to manufacturing processes is rarely documented. In particular, assessment of grinding technology regarding sustainability is still in its infancy.

Sustainability indicators are based on measured and/or estimated data that have to be normalized, scaled and aggregated consistently [5]. Research and applications of normalization are difficult to find. Therefore, this study discusses different normalization methods.

Most existing approaches and sets of sustainability indicators provide separate indicators with independent messages. The decision maker needs to compare between all aspects after the analysis. A quicker comparison is possible with a single sustainability indicator based on pre-chosen weighting factors. Therefore, this study proposes a method of merging the single indicators into a single value.

This paper assorts a small and manageable number of useful sustainability indicators for discrete manufacturing processes. It discusses different approaches to normalize these indicators. The paper shows then how the indicators can be displayed as a sustainability performance profile and as a total sustainability indicator calculated by utility analysis. In the end, the validity of the approach is proven for a grinding case study.

SUSTAINABILITY INDICATORS FOR DISCRETE MANUFACTURING PROCESSES WITH THE EXAMPLE OF GRINDING

Sustainability indicators need to capture the three dimensions of sustainability: social, environmental and economic. The indicators have to be specified in the following terms [3]:

- Period of tracking and calculating (e.g., fiscal year, calendar year, month)
- Boundaries (e.g., process level, factory level)
- Unit of measurement
- Type of measurement (e.g., absolute or adjusted)

In the following discussions, all sustainability indicators, *SI*, are normalized. In other words, they do not present their value as absolute amount but show relative terms as a ratio of performance per specific unit of output (equation (1)) [7]. The divisor is called normalization factor, *NF*, and discussed in detail in the following section. Thus, the indicators are presented as intensity.

$$SI = \frac{\text{Indicator}}{NF} \tag{1}$$

We consider the manufacturing process in the boundaries of Figure 1. The product design itself is not analyzed in depth, only through considering how the particular manufacturing process changes the product value, quality, and/or lifetime. This consideration is done through the use of an appropriate normalization factor as described in a later section.

It is advisable not to choose too many indicators in order to keep the analysis manageable. In addition, sustainability indicators should be independent of each other. In the following, we choose nine indicators from all three pillars of sustainability: environmental, economic, and social sustainability. Other indicator sets might have more or fewer categories [4]. We have the grinding technology in mind, because grinding is applied at the end of a manufacturing chain and therefore affects the part quality strongly. Furthermore, its complex process mechanisms limit the use of simplified formulas [8]. The sustainability indicators are selected to work on a process level and the necessary inventory can be done quickly.

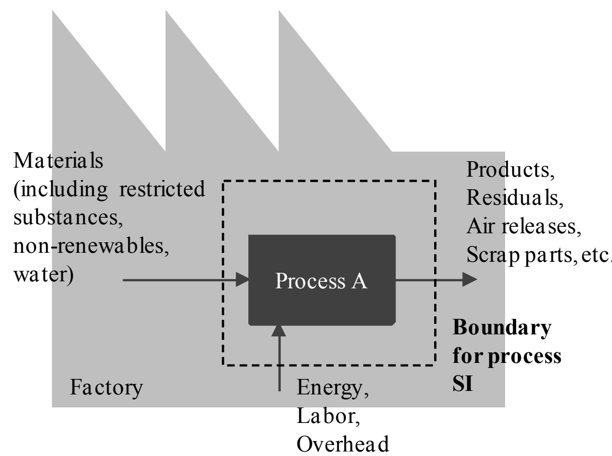

Figure 1. Boundary for evaluating a manufacturing process with process SI.

Environmental pillar of sustainability

All energy generation processes have an impact on the environment. Resources are consumed, greenhouse gases (GHG) are emitted, and waste is generated. On the way to a sustainable production, minimizing energy consumption is a central issue [9, 10, 11]. Energy is often used as a single stand-alone indicator for the assessment of environmental performance. In this study, the indicator **"Energy intensity"** measures the energy consumed in production processes and in overhead per normalization factor [7]. Normalization factors are described in the next section.

In general, residuals not only involve handling costs but also might have negative environmental influence [9, 10]. Reduction of waste improves profitability because of increasing efficiency due to a higher proportion of used material. The indicator **"Residuals intensity"** can be obtained either in a mass balance approach (weight of all inputs and fuel consumed minus weight of products) or waste output approach (weight of releases and transfers to air, surface water, land, landfill, disposal, treatment, recycling, energy recovery, sewage, GHGs produced plus carbon content of direct energy use) [7]. The result of the mass balance approach shows how many residues remain in the factory and must be disposed or recycled externally. The waste output approach calculates the waste output and adds up the quantities of all residuals that are actually generated. It is advisable to apply both approaches since a possible difference shows that the user might miss an important residual in the waste output calculation.

The indicator **"Non-renewable materials intensity"** describes and measures all inputs of non-renewable materials and shows the results with the unit tons per normalization factor. "Non-renewable materials" are defined as all resources that are finite [7]. Although water and fuels might be non-renewable materials as well, separate indicators for water and energy (fuel) consumption are given in this paper. The indicator includes materials without scarce supply (iron ore, copper, silver, etc.) and resources, which are evaluated as critical due to risks of maintaining supply (rare earths, rhodium, platinum, manganese, etc.) [7].

"Restricted substances intensity" provides a similar sustainability indicator, but consists of specific materials and resources restricted and limited by regulations and/or law [7, 9]. It must be the goal to reduce the use of critical resources by improvements in the process design or the reduction of waste.

The supply of water in sufficient quantity and quality is already one of the biggest challenges of our time and will become more important in the future. The consumption of water is not necessary in all production processes. However, water is often used for thermoregulation (cooling and heating) and/or washing processes. Oftentimes, it is not easy to substitute or reduce water use. The indicator **"Water intensity"** measures the intensity of total water intake of production processes and overhead of the facility [7, 9, 10].

Recent research on grinding has shown that industry often estimates the necessary cooling lubricant flow insufficiently [12]. In optimized processes, usage of less cooling lubricant often still allows stable machining and manufacturing of products with adequate quality [12]. Another approach is to reduce the water input stream by expanding and/or improving recycling within the boundaries of the considered system, e.g., through filtering systems.

Although the indicator "Residuals intensity" covers all residuals, releases to air should be accounted individually because they are very important to environmental pollution and human health [9, 10, 11, 13]. The indicator **"Intensity of pollutant releases to air"** measures and normalizes the weight of releases to air [7]. The following releases are of particular interest. Sulfur dioxide (SO_2) is mainly involved in the formation of acid rain, i.e. precipitation containing higher than normal proportion of sulfuric and nitric acids [14]. Particulate Matter (PM) is particles in the air, which do not immediately fall to the ground, but stay in the atmosphere for some time and cause respiratory problems [15]. Additional releases of interest are pollutants that are regulated, permitted or have priority for the state, region, local community, and public interest groups. Examples for this are NOx, SOx, persistent organic pollutants (POPs), volatile organic compounds (VOCs), and hazardous air pollutants.

Economic pillar of sustainability

"Grinding costs" or "Profits generated", i.e. the total net profits for a product [16], are sensitive sustainability indicators, because they lead to double accounting. Grinding costs add up from labor, energy, machine (maintenance, investment), room, tooling and coolant costs, but the definition can vary per factory. The grinding costs can also be split into single costs such as material acquisition costs, energy costs, tooling costs, labor costs, and waste treatment costs [9, 17, 18].

The user has to be aware that grinding costs account for many factors that might be addressed in other sustainability indicators such as auxiliary materials, tool wear, labor, scrap, waste. For example, the tool material appears in the residuals intensity but also in the grinding costs intensity. Double accounting also happens in the indicators labor intensity, energy intensity, water intensity, and productivity. Grinding costs are not chosen as an indicator here to avoid double accounting.

The indicator **"Investment costs"** can be useful, if new concepts are evaluated. The investment might be new machine tools, coolant supply systems, and/or filtration systems. If the investment encloses grinding tools, cooling lubricant and other auxiliary material for the grinding process, potential double-accounting might occur in the following indicators: residuals intensity, non-renewable materials intensity, restricted substances intensity, or water intensity. Return on investment (ROI) is a common economic metric, which takes the revenue from higher productivity into account. However, here we regard productivity separately.

"Productivity" can be expressed through machined material per time. The material removal rate is a first estimation, but the real productivity considers also auxiliary times and the process capability, i.e. how well the process stays within the tolerable boundaries. Boundaries can be set by the part surface roughness, for example, within the constraints of appropriate surface integrity and part dimensions. Process capability defines the rate of scrap parts, process dead times and quality costs. Auxiliary times are induced by machine set-up, tool reconditioning, part handling, worker break time and personal allowance, etc.

Social pillar of sustainability

Social sustainability and how it can be measured is a sensitive topic [19]. In this study, we focus on the manufacturing process itself and leave out overhead indicators such as “Human rights training for security personnel” [10], “Recordable injury rate” [18], “Blood lead level” [9], “Safety” [19]. We assume that all feasible measures are taken to keep workers safe, healthy, and educated.

The indicator **“Labor intensity”** accounts for the number of worker hours needed per normalization factor. This indicator could be adapted depending on the company strategy, for example by assessing the educational level of the workers per task. A company could aim to increase the ratio of highly educated workers and/or lower the ratio of labor per part. A related indicator is “(Labor) Productivity” defined as the ratio value of actual labor hours to planned labor hours for performing an operation or manufacturing a product [16]. The user has to be careful if the normalization factor includes the worker hours, because productivity is already a metric based on time.

NORMALIZATION FACTORS (NF)

Indicators should be normalized for better usability (equation (1)). Theoretically a wide variety of factors can be used to normalize performance [5]. Here, the following normalization factors are discussed [7]:

- Number, weight or units of products produced in the facility.
- Sales or value added in the facility.
- Person-hours worked in the facility.
- Lifetime of the products produced in the facility.

The following example visualizes the problems arising for different normalization factors. Two processes, A and B, are conducted on a part. The output for both processes is n products and we consider the energy intensity.

Number, Weight, or Units of Products Produced in the Facility

The first possibility is to divide the total amount measured by the number, weight, or units of products produced in the facility. Therefore, the basis is the output of production. For a comparison between different facilities or companies, an identical or similar product with identical or equivalent quality must be assumed. This way to normalize performance seems reasonable and comprehensible.

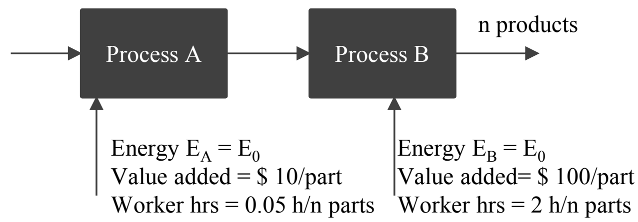

Figure 2. Example for two manufacturing processes A and B, adding values and consuming energy, $E_A = E_B = E_0$.

In the case study in Figure 2, the normalization factor can be the number of produced parts, *n*. The energy intensity, SI_A, per number of products produced would account to equation (2) for process A, and to equation (3) for process B. Because both processes produce the same number of products, *n*, with the same energy, $E_A = E_B = E_0$, both sustainability indicators are the same for the normalization via number of products produced in the facility (equation (4)).

$$SI_A = \frac{E_A}{NF_A} = \frac{E_0}{n} \tag{2}$$

$$SI_B = \frac{E_B}{NF_B} = \frac{E_0}{n} \tag{3}$$

$$SI_A = SI_B \tag{4}$$

With $NF_A = NF_B = n$

Sales or Value Added in the Facility

The second possibility is to evaluate the indicators by the added value or the sales. This approach is based on the supply chain and corresponds to the assumption that the aim of every company is to create value. By referring to the added value each process is captured in relation to its benefits. This approach seems particularly useful when comparing different processes within the production. It might be a challenge to detect the added value of single processes inside a company. In our example, the energy intensity per value added is ten times higher for process A (equation (5)) than for process B (equation (6) and (7)).

$$SI_A = \frac{E_A}{NF_A} = \frac{E_0}{\$10} \tag{5}$$

$$SI_B = \frac{E_B}{NF_B} = \frac{E_0}{\$100} \tag{6}$$

$$SI_A = 10 \cdot SI_B \tag{7}$$

With $NF_A = \$10$; $NF_B = \$100$; energies $E_A = E_B = E_0$

Person-Hours Worked in the Facility

Using the person-hours worked in the facility is a third option. This approach has similarities to the previous, if it is assumed that employees work to create value. A closer look into our example reveals potential weaknesses. The machine for process A is fully automated so an employee is only required for machine setup and maintenance, e.g., 0.05 h per batch. The machine for process B machines the same number of workpieces, but it requires one employee for the whole machining time, e.g 2 h per batch. With the same energy consumption and equal conditions assumed, the energy intensity per person-hours would be much higher for the automated process A (equation (8)) than for process B (equation (9) and (10)). This normalization factor might depreciate automated manufacturing.

$$SI_A = \frac{E_A}{NF_A} = \frac{E_0}{0.05\,h} \tag{8}$$

$$SI_B = \frac{E_B}{NF_B} = \frac{E_0}{2\,h} \tag{9}$$

$$SI_A = 40 \cdot SI_B \tag{10}$$

With NF_A = 0.05 h per batch; NF_B = 2 h per batch; energies $E_A = E_B = E_0$

Lifetime of the Products Produced

Another normalization factor is the lifetime of the products produced in the facility. Although we are analyzing manufacturing processes, the overall product lifetime and performance could vary a lot depending on the manufacturing operations applied. So the lifespan of the product has to be a central matter in any assessment of the sustainability of processes and products. The duration of the product`s life, i.e. how long a product can be used before it has to be disposed, recycled, or replaced with a new one, is hard to identify and strongly depends on the consumer [20]. Therefore, using the lifetime as normalization factor for all indicators does not seem reasonable.

Nevertheless, lifetime and product performance are important product quality measures defined by manufacturing. The concept of leveraging manufacturing grasps the fact that a higher resource demand in manufacturing can lead to a significantly improved product performance saving resources in the product use phase [21]. Examples include higher gear mesh efficiency through more energy intense grinding processes [22] or through an additional manufacturing step such as hard roller burnishing [23].

VISUALIZATION OF SUSTAINABILITY PERFORMANCE

The decision maker can either look into the SI data in detail or have a single value, SI_{total}, with predefined weighting factors. The method of utility analysis has proven to be very useful for this [24].

Visualization as Performance Profile Diagram

The sustainability performance profile can be displayed as a column diagram giving a special "foot print" per process. First, the evaluation criteria, here the sustainability indicators, are chosen. Because they are crucial for the final results, they need to be carefully planned and reviewed regularly. Dependencies and correlations between the criteria can affect the evaluation results drastically [25].

Then, the optimum value for each SI is determined. This optimum value sets the scale for the degree of fulfillment (DF). Usually, a simple scale e.g., 1-10 (very low fulfillment - optimal fulfillment), is used [25, 24]. Then the user has to determine the actual values for the sustainability indicators at his processes. Measured data is preferred to estimated data. Thereafter, the user ranks the values with a degree of fulfillment, *DF* (Figure 3, top). The degrees of fulfillment are self-contained and can be used in a qualitative comparison, e.g., in a column diagram (Figure 3 bottom).

$$\sum WF_1 + WF_2 + \ldots + WF_n = 100\% \tag{11}$$

With WF = weight factor

Visualization as Single Indicator

The utility value, *U*, is calculated with the degrees of fulfillment, *DF*, from Figure 3 (equation (12)).

$$U = DF * WF \tag{12}$$

With WF = weight factor

Each option has a total utility value, $\sum U_x$, as sum of all single utility values, U_{xi}, (equation (13)) (Figure 4).

$$\Sigma U_x = U_{x1} + U_{x2} + \ldots + U_{xm} \tag{13}$$

The total sustainability indicator, $SI_{total\,x}$, for each option is the percentage of the respective total utility value; $\sum U_x$, compared to a predefined option, $\sum U_{reference}$, (equation (14)) or to the maximum total utility value of all options, $max(\sum U_{xi})$, (equation (15)). Each option is represented by a single percentage value (Figure 4 bottom).

$$SI_{total\ x} = \frac{\Sigma U_x}{\Sigma U_{reference}} \tag{14}$$

$$SI_{total\ x} = \frac{\Sigma U_x}{\max(\Sigma U_a, \Sigma U_b, \ldots, \Sigma U_m)} \tag{15}$$

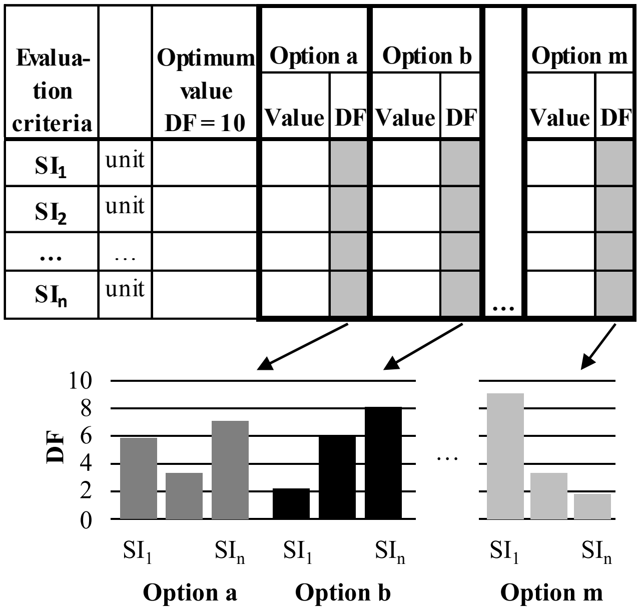

Figure 3. Sustainability performance profiles.

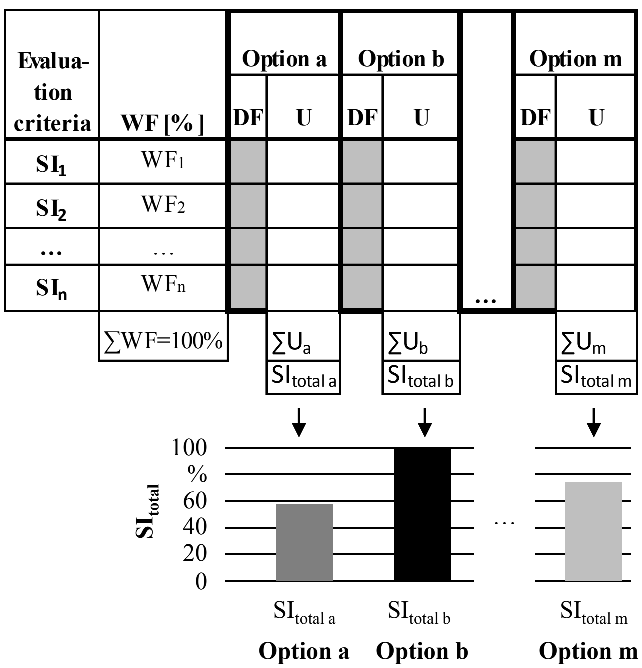

Figure 4. Total sustainability indicator.

CASE STUDY: GRINDING WITH CONVENTIONAL TOOLS VS. SUPERABRASIVE TOOLS

The case study evaluates two grinding strategies for an external cylindrical plunge grinding process of a seat at a gear shaft made of hardened steel. The two strategies are

1. grinding with a conventional grinding wheel (vitrified bonded alumina, emulsion as cooling lubricant, CNC machine tool with maximum wheel speed of $v_s = 63$ m/s),
2. grinding with a superabrasive grinding wheel (vitrified bonded CBN, grinding oil as cooling lubricant, CNC machine tool with maximum wheel speed of $v_s = 120$ m/s).

Here the normalization factor, *NF*, is chosen as a batch of 2000 machined gear shafts. This relates to industrial practice where costs and efforts are accounted to batches. In addition, necessary non-value adding steps such as machine set-up or tool conditioning and scrap parts occur only per batch, not per single part.

The values of the single sustainability indicators are displayed in Table 1 and are assessed as described in the following:

- "Energy intensity" consists of the processing energy, machine base and idle energy, and room energy costs such as HVAC.
- "Residuals intensity" consists of the input mass (pre-processed product, grinding wheels, cooling lubricant and additives, filter material, scrap, chips, tooling for wheel conditioning, etc.) minus the produced products. The waste output approach should add up to the same amount.
  For example, the intake of emulsion (strategy 1: conventional tool) is higher than oil (strategy 2: superabrasive tool) as cooling lubricant because of evaporation and lower life time of the emulsion. Moreover, the conventional tool wears much quicker than the superabrasive one.
- "Non-renewable materials intensity" includes the petroleum based coolant (strategy 2) and non-renewable grinding wheel ingredients in particular steel for the superabrasive wheel body, abrasive grit material, and most bond ingredients.
- "Restricted substances intensity" includes restricted substances in all materials, especially important for the grinding wheel ingredients or product material. An important case for tool grinding is for example cobalt leaching into the coolant. In this study, however, no restricted substances occur.
- "Water intensity" includes water in the cooling lubricant and possible subsequent cleaning processes. This is only the water that has to be replaced per batch.
- "Air releases intensity" includes PM and oil mist. Strategy 2 has higher wheel circumferential speed and produces more health relevant aerosols.
- "Investment costs" describes the necessary monetary investment for a new machine tool. The investment also includes the costs for grinding wheels, dressing equipment, coolant, and worker education.

- Strategy 2 works at a higher material removal rate because the higher wheel speed allows for higher feed rates [26]. Furthermore, the superabrasive grinding wheel can achieve a smaller roughness deviation and higher process stability and needs shorter reconditioning processes. “Productivity”, here given as specific material removal rate, considers the higher material removal rate, higher process stability, and lower auxiliary times for strategy 2.
- “Labor intensity” includes the worker hours per NF. Strategy 2 is applied at a highly automated machine tool and fewer auxiliary steps are carried out such as wheel exchange and conditioning.

The user has to find the optimum value for each SI, which can be as low as 0 and has a degree of fulfillment of 10 (Table 1, 3rd column). For energy intensity, there is a theoretical minimum energy resulting from the chip formation and the machine idle energy. All residuals, water and air releases intensities would equal 0 in the best case.

Investment costs and productivity are determined from the respective minimum values. Labor intensity depends on the specific factory and application setup for a highly automated process.

To compare the different sustainability indicators, each indicator is evaluated by the user by its degree of fulfillment, *DF*. DF = 1 is the worst degree of fulfillment, DF = 10 is the optimum. Figure 5 displays the sustainability performance profiles for the two compared grinding strategies.

The sustainability indicators rarely have the same relevance for the user and his company. Companies also might put more weight on economic sustainability rather than environmental and social sustainability. The cost benefit analysis allows for all scenarios with user-specific weight factors, *WF*. All WF add up to 100% (equation (11)). Table 2 shows an exemplary assignment of weight factors.

According to equation (12), the utility value, *U*, is calculated for each SI with the degrees of fulfillment, *DF*, from Table 1. The sustainability indicators for the ecological, economic and social pillar of sustainability are then calculated after equations (13) and (14). Figure 6 displays the ecological sustainability indicator, SI_{ecol}, economic sustainability indicator, SI_{econ}, and social sustainability indicator, SI_{soc}. It becomes obvious that the ecological performance of the superabrasive grinding strategy might be a bit worse than the conventional strategy, mainly because of higher energy and air releases intensities. However, the economic and social performances are much better for the chosen case study and weighting factors.

If the user decides to summarize all findings in only one total sustainability indicator, all utility values, *U*, are summed up (equation (13)) and scaled to the reference process, which is strategy 1 (equation (14)) (Table 2). Figure 7 shows the result in a column diagram. The higher SI_{total} of the strategy with the superabrasive tool results from the high relevance of economic sustainability (70 %) compared to ecological (25 %) and social (5 %) sustainability (Table 2).

Table 1. Case study: Comparison processes with a conventional grinding wheel and with a superabrasive grinding wheel.

		Optimum value	Conventional tool		Superabrasive tool	
		DF = 10	Value	DF	Value	DF
Energy intensity	kWh / NF	40	60	7	70	6
Residuals intensity	kg/ NF	0	500	7	210	2
Non-renewable materials intensity	kg/ NF	0	140	4	210	3
Restricted substances intensity	kg/ NF	0	0	10	0	10
Water intensity	l / NF	0	350	2	1	9
Air releases intensity	m^3 / NF	0	20	7	24	6
Investment costs	$	200k	200k	10	600k	2
Productivity	mm^3 / mms	15	5	5	10	10
Labor intensity	h / NF	12	20	6	12	9

NF = normalization factor

DF = degree of fulfillment, assigned by user 1: very low, negative 10: very high, optimal

Value and optimum value are assigned by user

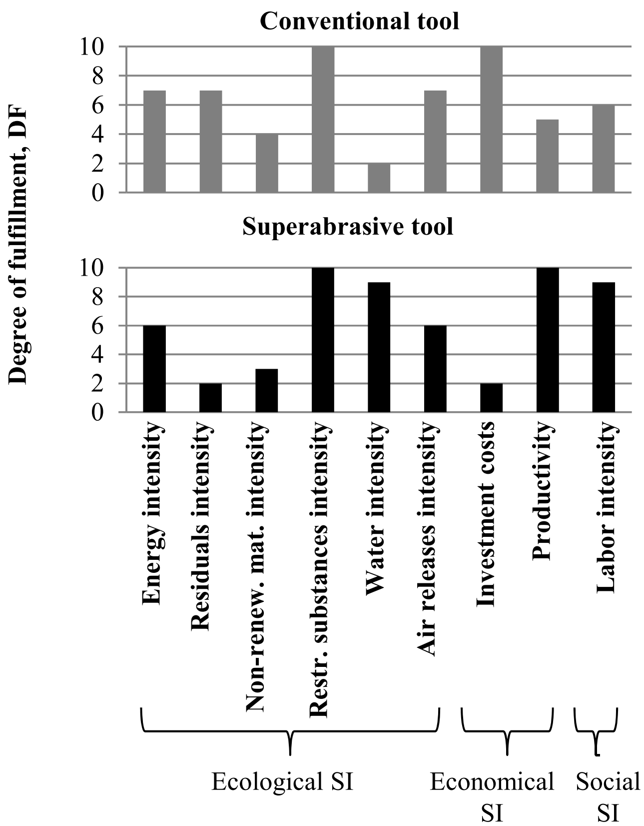

Figure 5. Case study: Sustainability performance profiles.

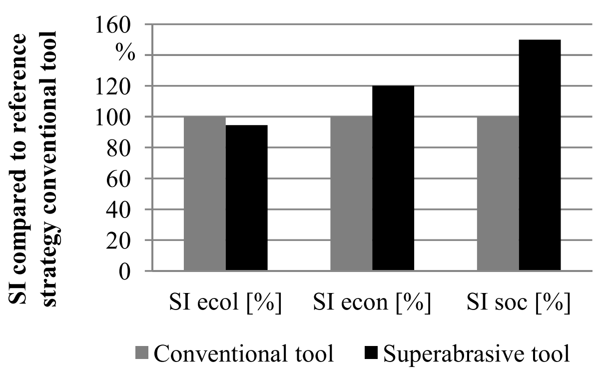

Figure 6. Case study: Ecological SI, SI_{ecol}, economic SI, SI_{econ}, social SI, SI_{soc}, individual to the company and application.

In industry, the high investment costs and necessary worker education might impede shifting to strategy 2. In addition, failure costs might be higher and flexibility is lower for the more expensive superabrasive tools, discouraging the investment.

Table 2. Case study: Ecological SI, SI_{ecol}, economical SI, SI_{econ}, social SI, SI_{soc}, global SI, SI_{total}, individual to the company and application.

		Conven-tional tool		Superabra-sive tool		
	WF [%]	DF	U	DF	U	
Energy intensity	9	7	63	6	54	
Residuals intensity	3	7	21	2	6	
Non-renewable materials intensity	3	4	12	3	9	
Restricted substances intensity	4	10	40	10	40	
Water intensity	3	2	6	9	27	
Air releases intensity	3	7	21	6	18	
		∑	163	∑	154	
SI ecol [%]	25		100	%	94.48	%
Investment costs	20	10	200	2	40	
Productivity	50	5	250	10	500	
		∑	450	∑	540	
SI econ [%]	70		100	%	120	%
Labor intensity	5	6	30	9	45	
		∑	30	∑	45	
SI soc [%]	5		100	%	150	%
		∑	643	∑	739	
SI_{total}			100	%	114.93	%

WF = weight factor, assigned by user

DF = degree of fulfillment, assigned by user

U = utility value, calculated as DF*WF

The resulting sustainability indicators depend on the subjective weighting factors. Table 3 displays a sensitivity analysis for each weight factor, *WF*. Here, the weight factor is assumed to vary by 3 % and the other weight factors are reduced or increased by the ninth part of 3 % accordingly to maintain a total sum of 100 % (see equation (11)).

The weight factors for water intensity and investment costs have the biggest impact on the overall sustainability indicator, SI_{total} (Table 3). This is because the degrees of fulfillment, *DF*, vary most for these categories between the cases conventional and superabrasive tool.

Table 3. Case study: Overall Sustainability Indicator for superabrasive tool compared to conventional tool depending on weight factor variation.

	WF [%]	SI_{total} (WF +3%) [%]	DSI_{total} (WF +3%) [%]	SI_{total} (WF) [%]	SI_{total} (WF -3%) [%]	DSI_{total} (WF -3%) [%]
WF (En. int.)	9	114.37	-0.56	114.93	115.49	0.56
WF (Res. int.)	3	112.31	-2.62	114.93	117.58	2.65
WF (N.-r.mat.int.)	3	114.60	-0.33	114.93	115.25	0.32
WF (Restr. s. int.)	4	114.66	-0.27	114.93	115.21	0.28
WF (Water int.)	3	118.98	4.05	114.93	111.03	-3.90
WF (Air rel. int.)	3	114.37	-0.56	114.93	115.49	0.56
WF (Invest. costs)	20	110.60	-4.33	114.93	119.45	4.52
WF (Productivity)	50	117.65	2.72	114.93	112.24	-2.69
WF (Labor int.)	5	116.52	1.59	114.93	113.34	-1.59

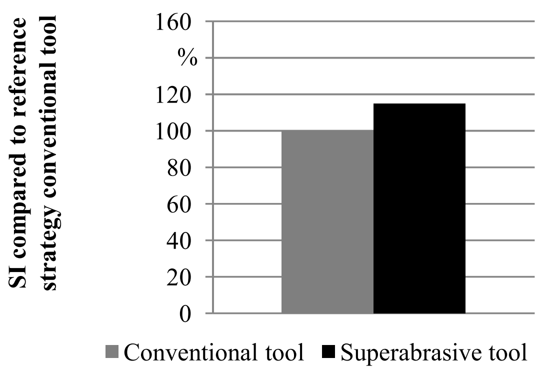

Figure 7. Case study: Total Sustainability Indicator, SI_{total}, individual to the company and application.

CONCLUSION

This paper shows a straightforward approach for evaluating discrete manufacturing processes with sustainability indicators. The advantage of sustainability indicators over more sophisticated methods like life cycle assessment (LCA) lies within the quicker data collection and easier display. Qualitative data can be used only with sustainability indicators. Nevertheless, the detailed information on larger scale effects is missing which is given through LCA and other methods such as ecotoxicity, impact on human health.

The evaluation of each indicator with a degree of fulfillment permits using qualitative and less detailed data. The utility analysis allows condensing the data into three sustainability indicators for each pillar and/or into one total sustainability indicator. The weighting is carried out individually for each company. This study shows the application of sustainability indicators on a manufacturing process level.

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