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Sustainability Indicators for Grinding Applied to Dressing Strategies

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Abstract:

Growing environmental awareness leads production engineers to focus increasingly on energy and material efficiency of manufacturing processes. However, only a few holistic approaches have been applied on the manufacturing process level and they often disregard product quality. In this study, sustainability indicators for the discrete manufacturing process of grinding are defined and discussed. Various temporal and spatial boundaries for the sustainability analysis are evaluated with regard to their effect on the results. Selected indicators, here energy and waste intensity, are then used to evaluate different dressing strategies in a case study. This study highlights the challenges in setting the boundaries for a sustainability analysis and stresses the importance of clearly defining these in research papers.

1. Introduction

Growing environmental awareness leads production engineers to focus increasingly on energy and material efficiency of manufacturing processes [1 - 5]. While sustainability commonly encompasses three dimensions, i.e. economic, environmental, and social sustainability [6], a fourth technological dimension needs to be considered in addition [7]. Moreover, sustainability in manufacturing covers not just the product and manufacturing processes involved, but also manufacturing systems, facilities, and the entire supply chain [8] with a geographic scope ranging from local to global [9].

Companies have to find ways to capture and measure their sustainability performance. The most commonly used method to evaluate environmental performance is the Life Cycle Assessment (LCA). One problem in using LCA, however, is the need for quantitative data - sometimes in great detail. Kellens et al. express the growing need for recent and high-quality data on manufacturing processes [10].

In addition to LCA, Life Cycle Costing (LCC) and Social Life Cycle Assessment (SLCA) are methods to evaluate the economic and social performance [6]. The multitude of interrelated system variables poses a challenge in assessing discrete manufacturing processes. Sustainability indicators provide a simple method to capture and evaluate all aspects of sustainability and they allow inferring conclusions on the phenomenon of interest [11 - 13]. Sustainability indicators are particularly useful for users with limited means and resources and can be applied on different levels, e.g. company, facility, process, or product level.

For example, Jawahir et al. defined process metrics for six dimensions including operator safety, personal health, environmental impact, cost, energy consumption, and waste management [8, 12]. An overall sustainability index allows for the summarization of several metrics into one value.

Feng et al. have built the NIST Sustainable Manufacturing Indicator Repository (SMIR), a comprehensive database on existing sustainability indicator sets [13 - 15]. This database offers access to more than 200 indicators sorted into five categories, which might be overwhelming for users who are looking for a quick assessment of a specific manufacturing application. Therefore, the following study focuses on the specific application of grinding technology.

Grinding is an important manufacturing step at the end of many process chains and affects product quality. This study defines and discusses appropriate sustainability indicators for grinding for the economic, environmental, social, and technological dimensions (section 2). The temporal and spatial boundaries for the sustainability analysis are discussed in section 3. On the one hand, the boundaries define the effort for conducting the analysis, i.e. in what detail does data need to be measured and collected. On the other hand, the boundaries determine the accuracy of results, for example by including or excluding outliers or defining the distribution range of data points. This is exemplified in a case study on two different dressing strategies in section 4.

2. Sustainability indicators for grinding

When assessing the sustainability of a grinding process a wide range of factors such as product material, non-product material (in particular the grinding tool and cooling lubricant), energy, waste, worker, and grinding machine must be taken into consideration [16]. The impact of each of these factors depends upon the application and process setup. Apart from this, abrasive machining can enhance product performance and increase service life (of parts). Thus it might be necessary to intensify efforts in the manufacturing phase and thereby increase the environmental impact of production, if this improves the product`s efficiency in the use phase to such an extent that the overall environmental impact is reduced [17, 18].

In this study, the sustainability indicators are chosen in accordance with today`s state of the art in grinding research [16, 19 - 23]. For better comparability, most indicators are normalized by number, weight, or units of products produced, value added in the process, lifetime of the products, or other useful normalization factors [11, 24, 25]. The indicators so turn into intensities. Normalization factors help to compare the measured indicators for different facilities, batch sizes, or even processes and they are chosen according to the businesses` interests [11]. For consistency, the normalization factor should be constant for the whole analysis [11].

Sustainability indicators can be compared individually and visualized in bar charts or grid diagrams giving an individual footprint for each application. For example, target plots display all indicators in one radar chart so quick comparisons are possible [26]. The Process Sustainability Index (ProcSI) regards the six clusters consisting of manufacturing costs, energy consumption, waste management, environmental impact, operator safety, and personnel health [12].

Instead of regarding all indicators separately it might be useful to concentrate them into one indicator. One method of summarizing a group of indicators into a single sustainability indicator is the use of utility analysis

[25]. Here, the user chooses the weight factors of each indicator. In another approach, Zhang and Haapala use Multi-Criteria Decision Making (MCDM) methods, in particular the outranking method PROMETHEE, to compare sustainability in different processing strategies [27].

The grinding process itself is complex, possesses many input and output streams and is thus difficult to model [28]. The dynamic nature of the process, in particular the grinding wheel wear, complicates modeling of process results and grinding energy [29]. Therefore, a completely theoretical approach is not feasible to evaluate grinding processes.

The sustainability indicators in this study include empirical data, which has to be obtained for the specific setup and environment. Nevertheless, the indicators relate to generic parameters, which have been derived with the help of an axiomatic grinding process model [30]. Axiomatic design is a method to describe systems and products systematically by generalizing the principles of the investigated system using self-evident truths [31]. This design method has been used to decompose the grinding process into basic functions and physical elements [30], which helped defining the sustainability indicators and clarifying the interconnections between economic, environmental, social, and technological dimensions.

2.1 Environmental dimension

In general, all incoming and outgoing resources of a process affect the environment. Thus useful sustainability indicators in the environmental dimension include energy and resource consumption, as well as process emissions [10]. For grinding in particular, product material, cooling lubricant, tooling, energy, and wastes are most important to be considered [16].

Grinding energy can be divided into processing energy for chip formation, machine energy for the base and idle state, and the background energy for handling, cooling, air suction systems, or other auxiliary systems (Eq. 1).

$$\text{Energy intensity} = \frac{\text{Processing energy} + \text{machine energy} + \text{background energy}}{\text{Normalization factor}} \tag{1}$$

Commonly, processing energy for chip formation is calculated from the grinding spindle power or from the tangential grinding forces and cutting speed [20]. Nearly all models on processing energy use empirical constants [28, 32]. For a given setup, Li et al. proposed a regression model for processing and machine energy depending on processing time or material removal rate [29]. This regression model is similar to milling process models [33] and has to be adjusted for each specific setup.

Depending on the operational boundary of the analysis, the energy of factory processes such as HVAC, lighting, office environment can be classified as background energy (scope 3 in Table 1). The production facility itself is a complex control system and the background energy it consumes has to be controlled to achieve overall energy efficiency, e.g. by technical measures, control of leakages and losses, or new energy concepts [34].

Similar to machining processes with geometrically defined cutting tools, energy consumption in grinding is mainly reduced either by shortening the processing time or by optimizing machine design [3]. Automated energy monitoring on the machine level supports technological sustainability by predicting machine component failures, process instabilities, or scrap parts, in addition to enhancing environmental sustainability and reducing scrap and failure costs [35].

Residuals intensity counts all waste created including fuel consumed onsite divided by the normalization factor [11]. In grinding, residuals include the removed product material (in the form of chips and debris), scrap parts, grinding tool (worn volume and dressed volume), coolant filter material, air filter material, consumed cooling lubricant, and evaporated refilled water, as well as dressing tool wear [16]. Cooling lubricants have been tackled in many studies and possess a high potential for improving process sustainability [16]. Depending on the application it is reasonable to account for water in a separate indicator due to its high relevance in many regions worldwide. Finite and non-renewable materials as well as restricted substances can also be evaluated separately [11]. Restricted substances are not likely to occur in common grinding processes but can be found in the REACH (Registration, Evaluation, Authorisation and Restriction of Chemicals) or OSHA (Occupational Safety and Health Administration) documentation of the used resources.

Substances released into the air through manufacturing processes are of importance for worker and community safety. In grinding, pollutant releases into air include aerosols from cooling lubricant, suctioned air, evaporated coolant, and particulate matter. Grinding wheel material, especially resin bonds, could also burn off, but this emission is assumed to be negligible. Greenhouse gas (GHG) emissions are not likely to result directly from the grinding process, but they occur as indirect emissions within scope 2 and 3 (see section 3, Table 1), and lie beyond the purview of this publication.

The key environmental sustainability indicators for grinding are energy intensity, residuals intensity, and intensity of pollutant released into the air.

2.2 Economic dimension

Useful economic sustainability indicators for grinding are grinding costs and productivity. Grinding costs per part are comprised of time-dependent and constant costs **(Fig. 1)**. Companies might not include all the aspects listed in Fig. 1 or they might consider additional costs, such as overhead and business travel costs. The time per part is defined as the sum of primary processing time and nonproductive time (**Fig. 2**). Grinding costs are not only of economic interest, but are often reliable indicators for overall sustainability, especially if the most relevant environmental, social, and technological factors are regarded and priced.

Productivity is defined as output per time for material removal rate or machined parts per time. Because the time-dependent costs commonly account for the highest proportion of the production costs, productivity affects the economic dimension significantly and is a simplified measure for economic sustainability.

Figure 1

Figure 2

2.3 Social dimension

Social sustainability applies to many different stakeholders, such as employees, customers, stockholders/owners, suppliers, the community, and the public [36]. Social sustainability indicators useful for grinding such as labor intensity, worker noise level, or hours of training and education per operator focus on the worker. Araujo and Oliveira found that while grinders have higher hourly wages and more hours of training than lathe operators, they also have a greater number of occupational accidents and are exposed to higher noise and operator risk levels [37]. The number of worker hours, hourly wages, or degree of automation are difficult indicators because they bear the rather philosophical question whether labor or low-cost wages should be avoided.

2.4 Technological dimension

Aside from the economic, environmental, or social sustainability, the user relies on the technological performance of the processes considered [7]. Few manufacturing processes are conducted without technological necessity, which stems from part function or the product`s aesthetics. However, different operations have varying impacts on product quality, which might not be directly measured in the other dimensions. Research is still needed to holistically grasp the connections between technology and the other sustainability dimensions. Useful technological indicators for grinding are product quality (e.g. surface structure or roughness, surface integrity), product performance and lifetime.

3. Boundaries of grinding process analysis

The functional unit of a life cycle assessment must be defined clearly and needs to be measurable [10]. Temporal and spatial boundaries determine the quality thereof [38]: the inclusion of more data yields a more comprehensive analysis with a higher the level of detail. In theory an omission of inputs or outputs is only recommended if it does not significantly change the overall conclusions of the study [10]. However, to evaluate the importance of particular data the researcher first needs holistic knowledge of all input-output streams. This is hard to accomplish in practice. Furthermore, individual companies can access only limited data along the supply chain. Therefore, a reasonable sustainability analysis requires simplifications.

Table 1 discusses different boundaries that must be taken under consideration when setting up a sustainability analysis. Temporal boundary I describes the period of data tracking, for example if the process data for the manufacturing of a single part or of a batch is monitored, or if data for one week of production is measured. Temporal boundary II defines whether only the product`s production or whole life cycle is regarded. The spatial boundary of the analysis can encompass either a single machine or an entire the factory and thus determines the physical space regarded therein. The operational boundary considers where the indicators occur: from the process directly, from energy production, or from producing raw materials for the process and the energy generation (Table 1). The scopes 1, 2, and 3 follow the GHG protocol [39].

Before choosing an appropriate boundary the challenges in Table 1 must be considered carefully. In addition, it needs to be communicated clearly to outside readers which boundary conditions apply.

The necessary life cycle inventory data, i.e. input-output streams to the process, can be acquired by measurements, by theoretical considerations, or as external or estimated data [10]. The chosen approach for data acquisition however affects the result tremendously, as shown by Duflou et al. for the example of processing energy [40]. For measured data, the transferability between different process setups is limited and the measurement can be demanding regarding equipment and time. In contrast, it is hard to account for process variability in theoretical considerations. The availability of estimated data or data from external databases may be limited and its quality heterogeneous. Databases often do not define the process setup sufficiently, which renders to transferability of data difficult.

4. Case study on conventional dressing strategies

Dressing is important for the technological performance of the grinding process. In terms of economic sustainability, the dressing process adds non-productive time and costs and consumes the grinding wheel, adding to the tool costs. In the case study discussed in this paper, the data was based on typical parameters and estimations (**Table 2**). This study is limited to energy and residuals intensity because these indicators have presumably the highest impact on sustainability and they reveal best how choosing different boundary conditions changes the results.

In a batch production, dressing intervals are hard to optimize and affect wheel performance and production time [41]. In this study, two dressing strategies were considered; strategy A entailed dressing after 10 parts, while dressing was performed after 25 parts in strategy B (**Fig. 3**). The grinding wheel has two wear states: Directly after dressing, wear behavior is affected mostly by the dressing conditions; after a certain period of time the grinding process conditions however dictate wear behavior [23, 42, 43]. This can be explained by the impact of the dressing forces on the grinding tool structure [44].

Figure 3

The grinding machine power is divided into base power, idle power, and processing power. Base power is the required constantly for the machine control and assumed to be 3 kW in this study. Idle power is variable over time and is consumed in the idle state of the machine when grinding spindle, pumps, and drives are running. Processing power is needed for chip formation (**Fig. 4**). For the grinding parameters of this study, the idle power is assumed to be 11 kW. Base and idle power are added yielding the so called tare power. Dressing power is assumed to be the same as tare power, because the dressing process takes place in the machine idle state. Besides, the stationary dressing tool does not need an additional spindle and the power for moving the dressing tool is neglected.

Figure 4

Figure 5 shows energy and residuals intensity for product production (temporal boundary II), one machine (spatial boundary), and scope 1 (operational boundary). Scope 1 focuses only on resources used in the grinding process, so that the study can be conducted independently from the location. Three temporal boundaries I were chosen: Product processing time, batch processing time, and one week.

Figure 5

The longer dressing intervals in B resulted in higher workpiece roughness deviation and more tool wear, which leads to a higher probability of scrap parts. This translates into lower process capability (e.g. process yield of 99.85 % for A, process yield of 99.75 % for B). However, strategy B also resulted in shorter batch processing time and likely lower grinding costs.

The temporal boundary of product processing time is comparatively short and thus does account for certain energies and residuals, such as for machine ramp-up, maintenance, filter mass, or debris mass (Fig. 5 top row). In contrast to longer time periods, however, only this scope allows to highlight that the processing energy varies depending on the tool wear state: The processing energy for strategy A varies between 14.1 – 16.6 kJ/part and for B between 14.1 – 17.7 kJ/part (error bars in Fig. 5 left upper diagram). Within the boundaries of a batch or week, average energy and residuals intensities are lower for strategy B compared to A. This results from the longer dressing times and higher grinding wheel consumption for strategy A. The lower average energy and residuals intensities indicate higher sustainability for strategy B. However, strategy B leads nonetheless to higher processing energies for some parts, which might result in higher thermal load. This leads to tensile stresses, surface layer damage, and lower workpiece quality [45].

When assessing longer time periods, longer processing times and higher energy intensities per part are monitored, due to unscheduled non-productive times being taken into account (Fig. 2). Thus time-dependent grinding costs are likely to be higher. The residuals from cooling lubricant are recorded in a temporal scope of a week (Fig. 5 bottom). Although only one machine is considered, it works with a central coolant supply and filtration. The flow rate of reused and filtered water can be changed on the process level, but the water intake depends on factory level decisions. Thus, only scope 2 and 3 water can be influenced by manufacturing process settings.

When temporal boundary II is extended to the product life cycle, the technological indicator of surface integrity becomes important. Parts produced with strategy A possess a potentially higher reliability in the use phase and longer life time. Cracks and mechanical failure are more likely for parts machined with higher grinding forces and grinding heat (strategy B) [46]. The overall sustainability in this case might be better for strategy A.

5. Conclusion

This paper discusses several appropriate indicators and boundaries for the sustainability analysis of grinding. Grinding technology presents special challenges to the temporal and spatial boundaries because it is applied at the end of a production chain and affects the product`s performance strongly. A case study on dressing showed the straightforward application of relevant sustainability indicators and clarified the challenges in setting the analysis boundaries. Longer tracking times likely result in more reliable data, but tool wear effects might be overlooked. A short tracking time can only be applied with a thorough and detailed consideration of all dominant indicators, even if they change outside of the temporal boundaries of the study.

Furthermore, the impact on sustainability might be different for the manufacturing phase versus the whole product life cycle. This means that the process strategy with the lowest energy, shortest processing time, and lowest costs might not be the best solution for the whole product life cycle. Obviously, this will get more important when producers become more responsible for the whole life cycle of their products. More research is however needed on linking product performance to manufacturing.

Standards for conducting sustainability analyses of grinding processes are needed and have not yet been defined. Research papers on sustainability need to clearly state the boundary conditions they apply. In addition, while some initiatives give advice on data acquisition and life cycle inventory, the chemical composition of the non-product materials and process stability over longer time periods have yet to be studied [10 - 12]. Furthermore, cooling lubricant, water or other auxiliary materials might not be defined by the discrete manufacturing process, but by factory level decisions.

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Nomenclature

a_{ed} = depth of dressing cut (mm)

b_d = active width of dressing tool (mm)

b_w = seat width (mm)

d_{w0} = initial diameter (mm)

d_{w1} = final diameter (mm)

e_{iA}, e_{iB} = energy per product (kJ)

$F`_t$ = tangential grinding force (N/mm)

m_{iA}, m_{iB} = residuals mass per product (mg)

P_{total} = power (kW)

$Q`_w$ = specific material removal rate (mm^3/mms)

U_d = dressing overlap ratio (-)

v_s = wheel speed (m/s)

V_w = material removal (mm^3)

Δr_{gw} = radial wear (μm)

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Table 1

	Range	Challenges
Temporal boundary I	Product processing time	The period might be too small to estimate process deviations or process capability. Auxiliary and failure times are often underestimated. Outliers have a big effect on results.
	Batch processing time	The analysis is well manageable, but auxiliary processes have to be taken into account carefully. Outliers have a big effect on results.
	Week / month / year	Data specified to single products or processes might not be available.
Temporal boundary II	Product production	This scope might not display Total Cost of Ownership (TCO) for the product.
	Product life cycle	This scope needs higher analysis effort. Data for future product use and end of life might not be available. Furthermore, use phase conditions and user behavior change the lifetime of products.
Spatial boundary	One machine	Some peripheral processes are left out (transport, handling, cleaning steps, etc.).
	Factory	Data might include other manufacturing processes or business activities.
Operational boundary after [39]	Scope 1	Scope 1 includes direct resources from the discrete manufacturing process.
	Scope 2	Scope 2 includes indirect resources from consuming purchased electricity, heat, or steam. This data can be obtained from databases based on regional averages.
	Scope 3	Scope 3 includes further indirect resources, such as for extraction and manufacturing of purchased materials, fuels, equipment, waste disposal, etc. Some of this data might be available in databases.

Table 2

Workpiece	**Cooling lubricant**
Gearshaft seat made of steel 100Cr6 (AISI52100)	Emulsion, 4% oil
Start diameter d_{w0} = 50.1 mm	Volume = 20,000 L (central supply)
End diameter d_w = 50 mm	Replacement after chip mass of 1 t is taken in
Seat width b_w = 20 mm	By the time of replacement, 2,000 L of water were refilled due to evaporation.
Grinding tool	**Dressing process**
Al_2O_3 grit (F100) in vitrified bond	Diamond dressing tile
Dimensions 400 x 20 x 200 mm	Active width of dressing tool b_d = 0.8 mm
Grinding parameters	Overlap ratio U_d = 4
Wheel speed v_s = 45 m/s	Depth of cut a_{ed} = 10 µm
Specific material removal rate (MRR) $Q`_w$ = 2 mm^3/mms	Movement time of grinding wheel to dressing position = 2 s
Batch size of 500 workpieces	Overrun time of grinding wheel per dressing stroke = 0.5 s
Handling time per part = 1 s	Number of dressing strokes needed to restore wheel profile = integer value (radial wheel wear/a_{ed}) + one additional stroke

Fig. 1

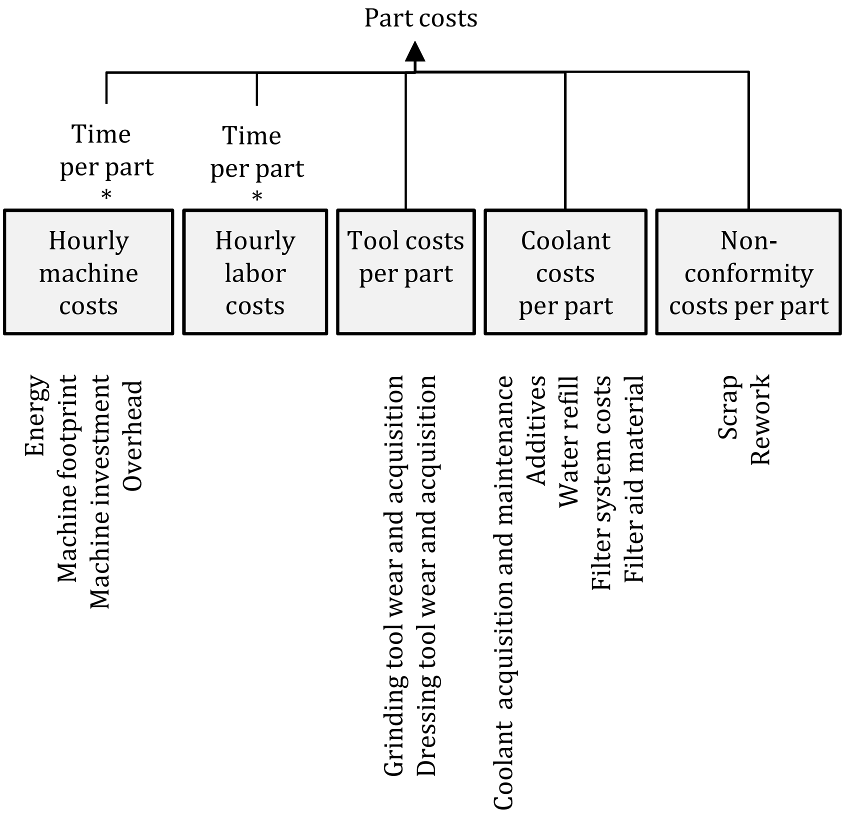

Part costs
Time per part *
Time per part *
Hourly machine costs
Hourly labor costs
Tool costs per part
Coolant costs per part
Non-conformity costs per part
Energy
Machine footprint
Machine investment
Overhead
Grinding tool wear and acquisition
Dressing tool wear and acquisition
Coolant acquisition and maintenance
Additives
Water refill
Filter system costs
Filter aid material
Scrap
Rework

Fig. 2

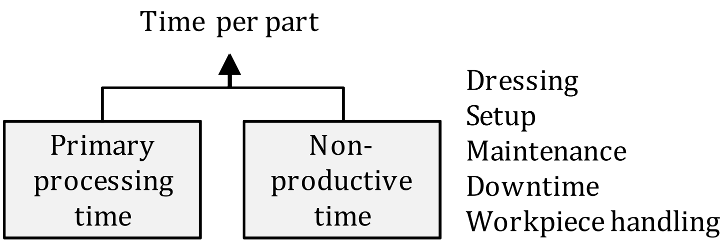

Time per part
Primary processing time
Non-productive time
Dressing
Setup
Maintenance
Downtime
Workpiece handling

Fig. 3

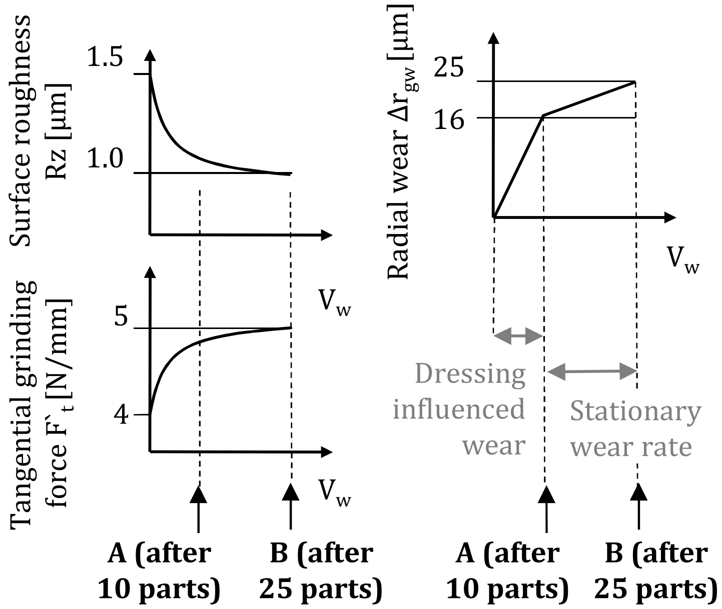
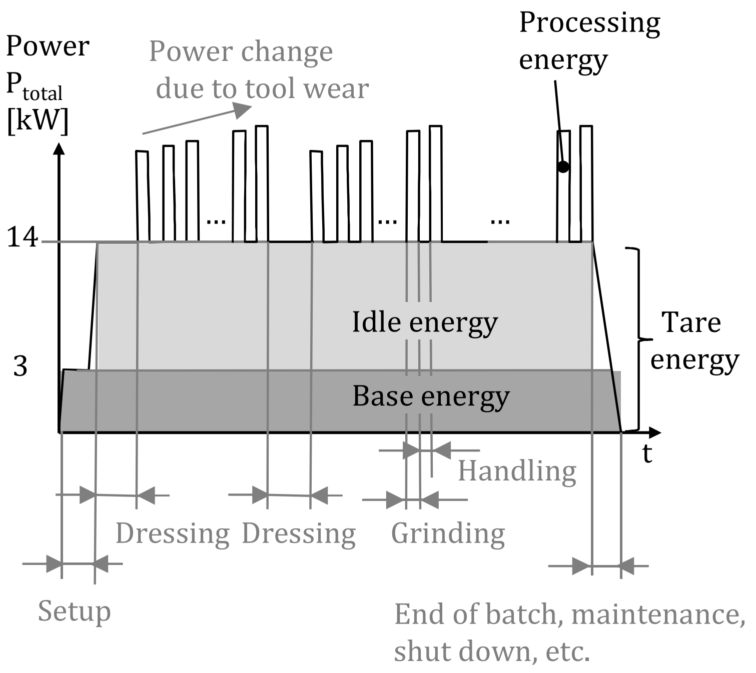
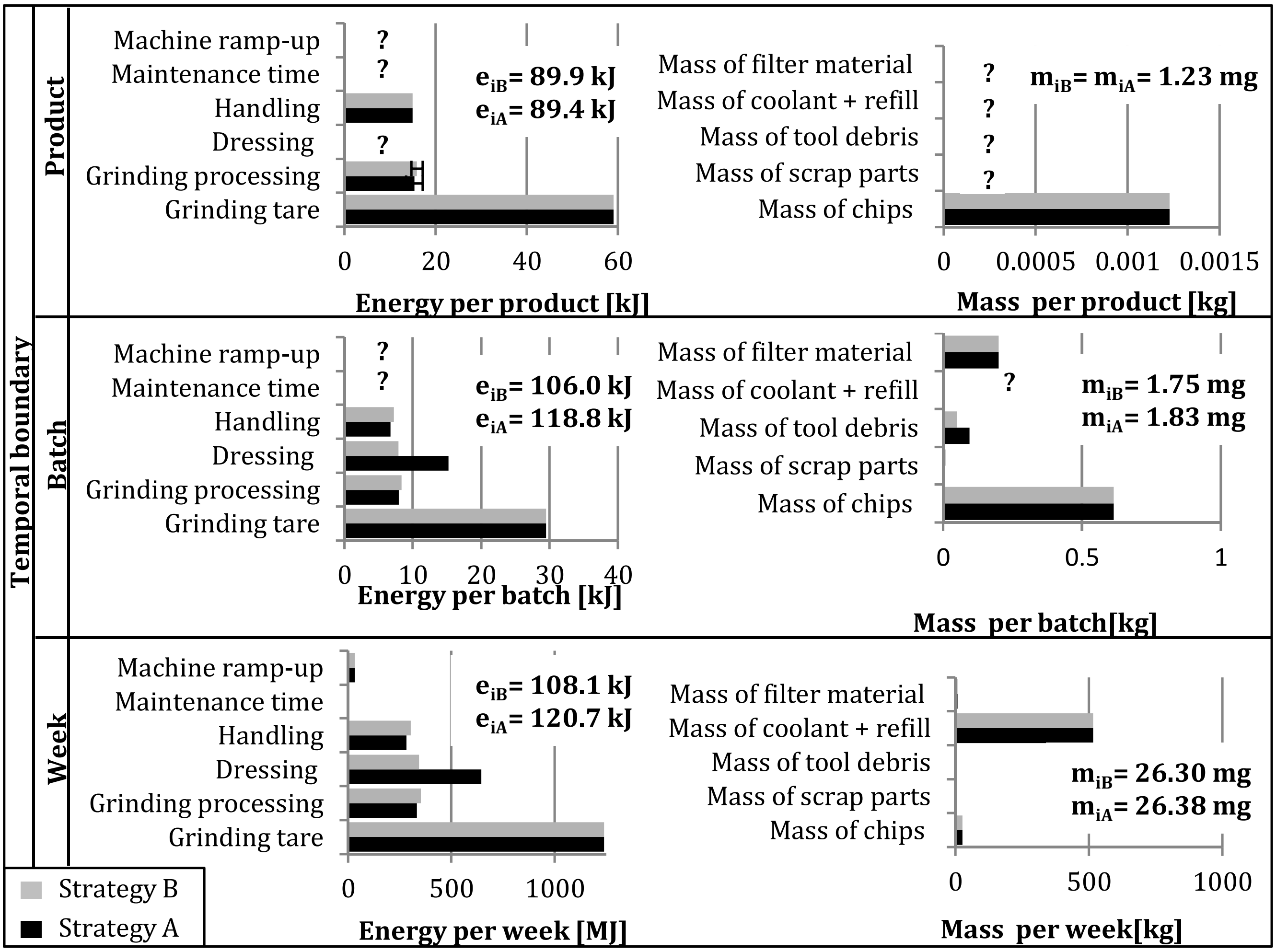

Surface roughness Rz [µm]
1.5
1.0
Tangential grinding force F`t [N/mm]
5
4
Vw
Vw
Radial wear Δrgw [µm]
25
16
Vw
Dressing influenced wear
Stationary wear rate
A (after 10 parts)
B (after 25 parts)
A (after 10 parts)
B (after 25 parts)

Fig. 4



Processing energy
Power P_{total} [kW]
Power change due to tool wear
14
3
Idle energy
Base energy
Tare energy
t
Handling
Dressing
Dressing
Grinding
Setup
End of batch, maintenance, shut down, etc.

Fig. 5


Temporal boundary
Product
Machine ramp-up
Maintenance time
Handling
Dressing
Grinding processing
Grinding tare
?
?
?
e_{iB}= 89.9 kJ
e_{iA}= 89.4 kJ
0
20
40
60
Energy per product [kJ]
Mass of filter material
Mass of coolant + refill
Mass of tool debris
Mass of scrap parts
Mass of chips
?
?
?
?
m_{iB}= m_{iA}= 1.23 mg
0
0.0005
0.001
0.0015
Mass per product [kg]
Batch
Machine ramp-up
Maintenance time
Handling
Dressing
Grinding processing
Grinding tare
?
?
e_{iB}= 106.0 kJ
e_{iA}= 118.8 kJ
0
10
20
30
40
Energy per batch [kJ]
Mass of filter material
Mass of coolant + refill
Mass of tool debris
Mass of scrap parts
Mass of chips
?
m_{iB}= 1.75 mg
m_{iA}= 1.83 mg
0
0.5
1
Mass per batch[kg]
Week
Machine ramp-up
Maintenance time
Handling
Dressing
Grinding processing
Grinding tare
e_{iB}= 108.1 kJ
e_{iA}= 120.7 kJ
0
500
1000
Energy per week [MJ]
Mass of filter material
Mass of coolant + refill
Mass of tool debris
Mass of scrap parts
Mass of chips
m_{iB}= 26.30 mg
m_{iA}= 26.38 mg
0
500
1000
Mass per week[kg]
Strategy B
Strategy A