Chapter 2
Grinding, Modelling and Eco-efficiency

Abstract This chapter presents the theoretical foundations of this work. Firstly, the basics of the grinding process and the elements of the grinding system are illustrated. Secondly, modelling approaches and indicators are described. Lastly, the origin, definitions and approaches on how to achieve eco-efficiency are presented. The chapter ends with a preliminary conclusion.

2.1 Grinding as a Production Process

DIN 8589 defines the term grinding, as machining with a tool whose number of cutting edges, rake angle geometries and position of cutting edges to the workpiece surface is not defined (DIN 8589-0 2003, p. 4). Therefore, the term describes the application of track-bound hard materials, which differ slightly in their irregular shape and in their relative position to each other, for the machining of materials.

In industrial countries, the production process grinding accounts for 20–25 % of the total expenditure of all machining processes (Malkin and Gou 2008, p. 1). In 2009, 28 % of all the installed CNC machine tools (about 750.000) in the European Union (EU27) were grinding machines (Schischke et al. 2012c, p. 12ff.). Grinding is applied either to attain high material removal rates or to achieve defined surface qualities, accuracy and certain workpiece characteristics. In both cases, it is commonly applied for the machining of hard-to-cut materials (Rowe 2009, p. 2f.; Marinescu et al. 2007, p. 3ff.), such as hardened steel, aerospace alloys, ceramics and cemented carbide (Rowe 2009, p. 2).

The production of almost every technological product is either directly or indirectly connected with the grinding process (Malkin and Gou 2008, p. 1). The direct connection arises as a result of the grinding process being applied at certain stages of the manufacturing process. Typically, grinding is one of the last manufacturing steps in the production chain. The process can be used to achieve high accuracy while machining hard materials. The machined parts are very valuable, and defects due to grinding can lead to high costs (Rowe 2009, p. 4). The indirect

M. Winter, *Eco-efficiency of Grinding Processes and Systems*,
Sustainable Production, Life Cycle Engineering and Management,
DOI 10.1007/978-3-319-25205-6_2

connection arises due to the impact of the grinding process on the accuracy of other machining processes, such as milling, turning or drilling, owing to the application of the grinding process in the production of components (e.g. bearings, guides, gears) as well as tools (e.g. drills, cutting inserts) for these machine tools.

Nonetheless, grinding is in competition with other machining processes, such as turning or milling. When it comes to achieving high volumes of removed material, the grinding process has lower economic and technological productivity than the milling and turning processes. However, due to the emergence of near-net shape production techniques (for example precise casting and forging), the need to remove high volumes of material decreases and grinding becomes again a viable option to increase process productivity by achieving the desired geometry in one machining process without prior turning or milling processes (Malkin and Gou 2008, p. 3).

Grinding is a key technology to meet predefined technological requirements. However, its application needs to be considered in connection with economic and environmental boundaries set by customers, competitors, public institutions, etc. To achieve a high-quality grinding process combined with a low economic and environmental impact, knowledge about the process as well as the necessary demand of energy and resources is needed.

Levels of Grinding

Grinding is performed within a system consisting of different subsystems and components. In accordance with DIN 25424-1, the following terms can be identified (DIN 25424-1 1990, p. 2):

- **System (overall)**: “an aggregation of technical-organisational means for the autonomous realisation of a complex of tasks” (e.g. grinding machine),
- **Subsystem**: “a combination of components, to solve an associated task within a technical system” (e.g. turret wheel head),
- **Component**: “the smallest item under consideration of a technical system. One or more functional elements are related to each component” (e.g. spindle drive) and
- **Functional element**: “the smallest item under consideration in a functional system. It can only describe one elemental function” (e.g. commutator ring inside the spindle).

By using the system theory, relationships between these terms can be described. Ropohl defines three system concepts: the functional, the structural and the hierarchical (Ropohl 2009, p. 75). These concepts are convertible into each other: functional purposes, for example, can be described using a structure that is part of multiple hierarchical levels. Therefore, the functions define the structure and the hierarchy of the system (Ropohl 2009, p. 77).

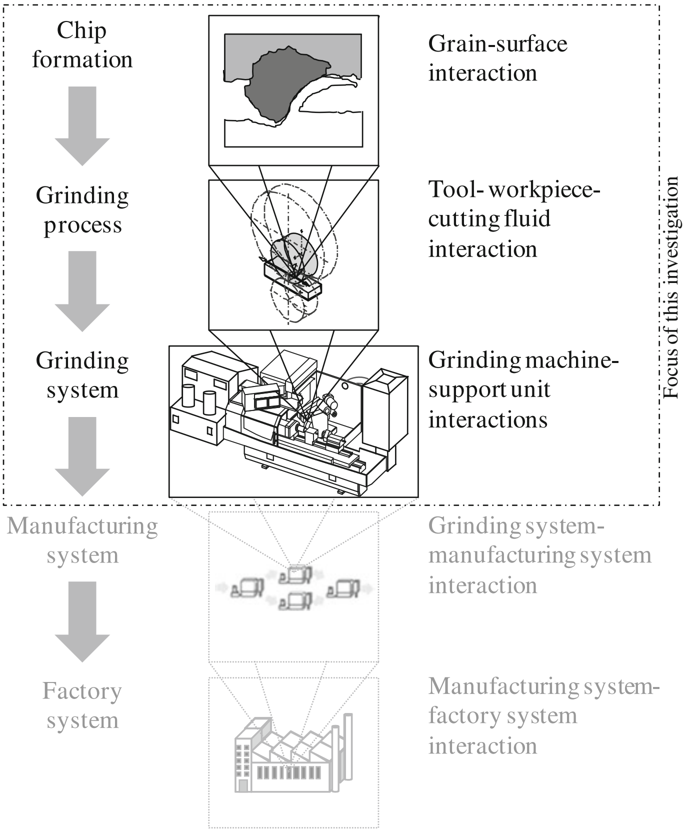

Fig. 2.1 Hierarchical levels in grinding

Different hierarchical levels and corresponding systems can be found in grinding. Each of these systems can be expressed as a subsystem, consisting of components and functional elements of another system (Fig. 2.1).

The lowest system level is chip formation, characterised by the grain—surface interaction. Chip formation is part of the next level, the grinding process, consisting of the tool–workpiece–cutting fluid interaction. This system is incorporated into the grinding system, including a grinding machine–support unit interaction. The next, higher level is the manufacturing system, which represents a subsystem of the factory system. Both structural system concept and functional concept can be used to describe the independency of different systems if these are unknown. In the next sections, chip formation, grinding process and grinding system are described in detail.

2.1.1 Chip Formation

The material removal process is based on an enforced sequence of randomly located single cutting edge engagements with the workpiece surface material. The engagement depends on the predominant geometrical and kinematical relationships (Werner 1971, p. 12).

The cutting edge is located on the abrasive grain, which moves along a fixed grain path and penetrates the workpiece with a flat attack angle (α). The abrasive grain interacts with the workpiece in three phases to achieve chip formation. Each phase is characterised by a different contact type (Fig. 2.2). In the first phase (I), an elastic deformation of the workpiece occurs, due to the rubbing of the grain on the workpiece surface. With increasing intrusion in the second phase, the grain ploughs into the workpiece surface resulting in an additional plastic deformation (II). After exceeding a critical intrusion depth, the cutting process and the chip formation occurs (III), leading to a chip with a specific thickness (h_{cu}) (Klocke 2009, p. 8/9; Rowe 2009, p. 341ff.).

During chip formation, energy is needed in the mechanical processes (cutting, ploughing and rubbing) for surface generation. Compared to cutting processes with geometrically defined cutting edges, the abrasive processes have a higher specific energy demand for the removal of one unit volume of material (Malkin and Guo 2008, p. 120). This is due to the aforementioned undefined number, shape and position of cutting edges. Almost all of the specific energy is converted into heat, and only a minor share is used to form the material or to accelerate the chips (Rowe 2009, p. 370). The degree of energy demand depends on the predominant geometrical and kinematical relationships between grinding wheel and workpiece, as well as on the physical and chemical composition of the grinding process (grinding wheel, cutting fluid and workpiece). These components are described in the next section.

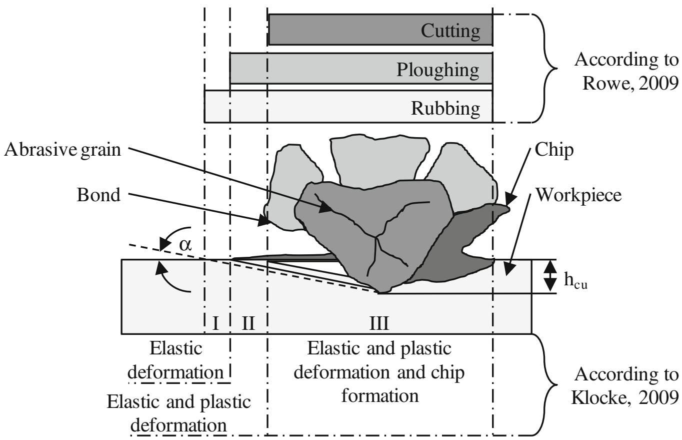

Fig. 2.2 Phases of chip formation and underlying contact types [(Linke and Dornfeld 2012, p. 415) (based on Klocke 2009, p. 8; Rowe 2009, p. 341ff.)]

2.1.2 Grinding Process

The predominant geometrical and kinematical relationships and the related parameters are presented in Fig. 2.3 for the following orthogonal grinding process types: internal cylindrical grinding, external cylindrical grinding and surface grinding.

The input parameters of the grinding process result from the following geometrical and kinematical relationships: cutting depth (a_e), cutting speed (v_c) and workpiece speed (v_w). In the case of internal and external cylindrical grinding processes, the reference point (*G*), located on the grinding wheel, moves nominally on a cutting depth-dependent arithmetic spiral into the workpiece (if the workpiece speed is constant).

The workpiece speed (v_w) (Eq. 2.1) and grinding wheel speed (v_s) (Eq. 2.2) are calculated based on the rotational speed of the workpiece (n_w) and grinding wheel (n_s) at the workpiece diameter (d_w) and grinding wheel external diameter (d_s), respectively. Equations (2.1) and (2.2) follow the approximation that the grinding wheel speed (v_s) equals the cutting speed (v_c) (Böge 2007, p. 368).

$$v_w = \pi \cdot n_w \cdot d_w \tag{2.1}$$

$$v_s = \pi \cdot n_s \cdot d_s = v_c \tag{2.2}$$

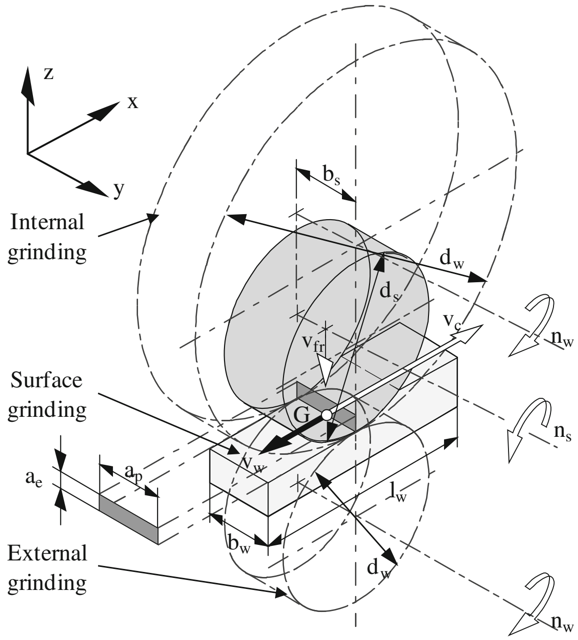

Fig. 2.3 Geometrical and kinematical relationships in orthogonal grinding processes (based on Saljé and Möhlen 1986, p. 249)

An important key figure in describing the grinding process is the material removal rate (Q_w) (Eq. 2.3) and the specific material removal rate (Q'_w) (Eq. 2.4). Both values describe the material removed per second; however, the latter also describes the amount related to 1 mm cutting width (a_p).

$$Q_w = v_w \cdot a_e \cdot a_p \tag{2.3}$$

$$Q'_w = \frac{Q_w}{a_p} = v_w \cdot a_e \tag{2.4}$$

2.1.2.1 Grinding Wheel

The structure and composition of the grinding wheel is dependent upon the material to be machined, the necessary material removal rate as well as the required workpiece accuracy and surface quality. It is commonly composed of up to four components: abrasive grains, bond, pores and (depending on the grinding wheel design) wheel hub. The bond links and embeds the abrasive grains. The pores are either naturally created due to the irregular shape and the intergranular space between the abrasive grains or artificially induced by pore builders. The task of the pores is the transport of chips and cutting fluid (Davis 1995, p. 112). The grinding wheel can be classified according to bond type, abrasive material and structure.

The classification of the grinding wheel according to the bond system includes the options of vitreous, organic/synthetic resin, metallically sintered and electroplated bond systems (Davis 1995, p. 110ff.; Klocke 2009, p. 37ff.). With conventional abrasives and super abrasives, two abrasive grain material groups can be distinguished. Conventional abrasives include grains made from black or green silicon carbide and zirconia alumina as well as fused or non-fused aluminium oxide. Super abrasive grains are made either from synthetic diamond or cubic boron nitride (cBN). The hardest abrasive is diamond, followed by cBN, silicon carbide, aluminium oxide and zirconia alumina (Davis 1995, p. 101ff.; Klocke 2009, p. 17ff.). The worldwide production amount of the four abrasive types indicates a broad use of conventional abrasives. The annual production quantity and the mean production energy demand for aluminium oxide, silicon carbide, cubic boron nitride and diamond are presented in Fig. 2.4. In 2013, about 1.19 million tons of aluminium oxide and about 1 million tons of silicon carbide abrasive materials were produced (USGS 2014, p. 13). The amount of super abrasive materials produced was comparably lower, with about 25.1 tons of cubic boron nitride (year 2008) (McClarence 2010, p. 2) and about 33.63 tons of synthetic diamond (year 2005) (Bain and Company 2011, p. 81). The processing of conventional abrasives made of aluminium oxide (purity 99.5 %) demands about 49.5–54.7 MJ/kg and of abrasives made of silicon carbide 70.2–77.6 MJ/kg (Granta Design 2010). The production of super abrasive grains made of cubic boron nitride is connected with an energy demand of 490 MJ/kg (Winter et al. 2015, p. 13). The production of

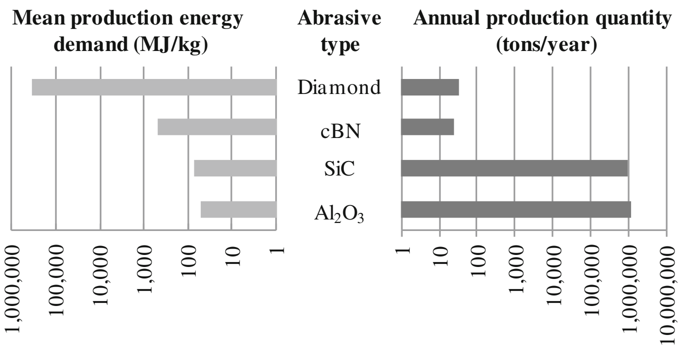

Fig. 2.4 Overview of the mean production energy demand and annual production quantity of different abrasive types (logarithmic scale) (based on USGS 2014, p. 13; McClarence 2010, p. 2; Bain and Company 2011, p. 81; Granta Design 2010; Winter et al. 2015, p. 13; Ali 2011, p. 3)

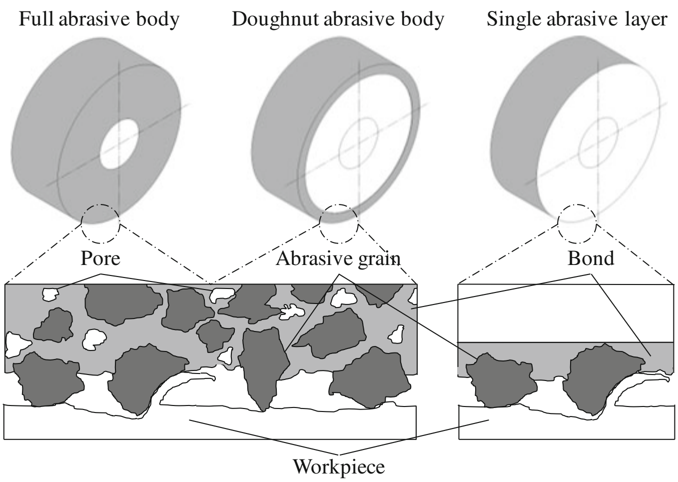

Fig. 2.5 Structure of grinding wheels (Wegener et al. 2011, p. 758)

synthetic diamonds was reported with circa 360 GJ/kg of processing energy (Ali 2011, p. 3).

The grinding wheel structure is divided into a full abrasive body, a doughnut abrasive body and a single abrasive layer (Fig. 2.5). The full abrasive bodies are made of conventional abrasive materials, while super abrasive materials are commonly used in the doughnut-shaped abrasive body or as a single abrasive layer coated on a wheel hub. These variations are due to the availability and costs of the various abrasive materials.

2.1.2.2 Conditioning Process

The preparation and regeneration of the grinding wheel's macro- and micro-geometry prior and during its application is referred to as the conditioning process, also commonly defined as dressing process. The term conditioning includes the processes of cleaning and dressing, while the dressing process can be further classified into profiling and sharpening (Wegener et al. 2011, p. 758; Klocke 2009, p. 135ff.). Different conditioning processes (mechanical, thermal, chemical or hybrid) can be applied depending on the grinding wheel bond and abrasive type (Wegener et al. 2011, p. 757ff:). Usually, mechanical conditioning processes are applied in industrial grinding processes by using a form or profile conditioning kinematic with either fixed or rotating tools (Wegener et al. 2011, p. 759; Saljé 1991, p. 14) (Fig. 2.6).

The mechanical conditioning process presented in Fig. 2.6 is described by the dressing depth (a_{ed}), the dressing tool radius $\left(r_{pd}\right)$ and the traverse dressing lead (f_{ad}), as well as the effective dresser width (b_d), the axial dressing overlap $\left(a_{pd}\right)$ and the traverse dressing speed $\left(v_{fad}\right)$. When a rotating dressing tool is used, the rotational speeds of dressing tool (v_d) and grinding wheel (v_c) are also taken into account (Fig. 2.6).

The dressing overlap ratio can be obtained (U_d) based on the aforementioned variables (Eq. 2.5). The dressing overlap ratio describes the smoothness of the surfaces of the grinding wheel, which is due to the distance between the grooves created by the dressing tool. A high value indicates a finely dressed grinding wheel and a low value a coarsely dressed grinding wheel surface (Klocke 2009, p. 135ff.; Messer 1983, p. 17ff.).

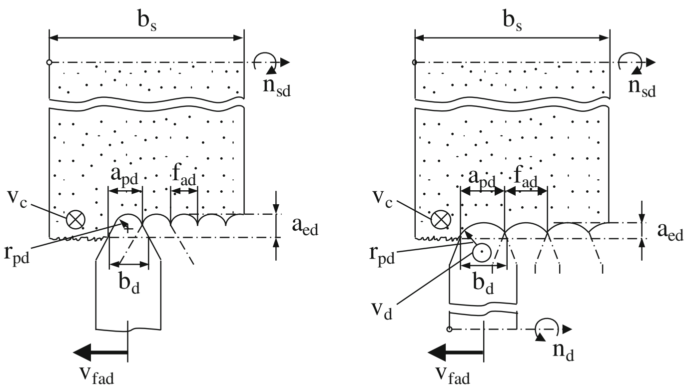

Fig. 2.6 Geometric and kinematic relationships in conditioning processes. **a** Fixed dressing tool. **b** Rotating dressing tool

$$U_d = \frac{b_d}{f_{ad}} \tag{2.5}$$

The dressing speed ratio (q_d) can be calculated by relating dressing tool and grinding wheel speed (Eq. 2.6). The dressing speed ratio influences the length of the engagement path of the dresser in the grinding wheel and therewith the created grinding wheel topography (Klocke 2009, p. 158; Schmitt 1968, p. 55).

$$q_d = \frac{v_d}{v_c} \tag{2.6}$$

2.1.2.3 Cutting Fluid

During the grinding and conditioning process, the application of a cutting fluid is indispensable. The main task of the cutting fluid is to lubricate and/or to cool the processing zone (DIN 51385 2013, p. 4; VDI 3397-2, p. 3f.). A cutting fluid contains two main components: a base fluid and additives. According to DIN 51385, the base fluid is generally divided into non-water miscible and water miscible fluids (Fig. 2.7) (DIN 51385 2013, p. 4).

Non-water miscible cutting fluids are commonly mineral oil-based fluids, enfolding solvent neutrals (paraffinic or naphthenic) and hydrocrack oils. However, vegetable oils and animal fats, containing chemically untreated and treated (ester) fluids, as well as synthetic base oils (polyalphaolefines or polyalkyleneglycos) are also used (Möller and Nassar 2002, p. 72ff.; Silliman 1992, p. 36f.). Water miscible fluids are classified into emulsions and dilutions. An emulsion is a milky and stable disperse mixture, created by the emulsification of mineral base oils, vegetable oil esters or animal fat esters into water. Dilutions generally represent chemically stable and clear fluids composed of water and inorganic and/or organic substances (Möller and Nassar 2002, p. 568ff.; Brinksmeier et al. 1999, p. 583).

Additives are used to improve or constrain specific fluid characteristics (Möller and Nassar 2002, p. 563ff.; Schulze and Holweger 2010, p. 76ff.). Additive-free base fluids can only be used as cutting fluids considering specific restrictions, because the geometry of chip formation as well as high pressures and temperatures prevents a separation of the friction surfaces (Möller and Nassar 2002, p. 563ff.). Additives are necessary to excite physical and chemical reactions, which enable easily shearable boundary layers (Möller and Nassar 2002, p. 563ff.). Accordingly, additives can be classified into enhancers of physical and/or chemical fluid characteristics as well as in tribologically active additives (Hipler et al. 2000, p. 5). Wear protection additives include polar-additives, extreme-pressure-additives and anti-wear-additives. Other additives are agents against corrosion, foaming, oxidation, etc. The additive content in a cutting fluid depends on the application case and varies between a few parts per million up to 20 % of the total (Hipler et al. 2000, p. 6).

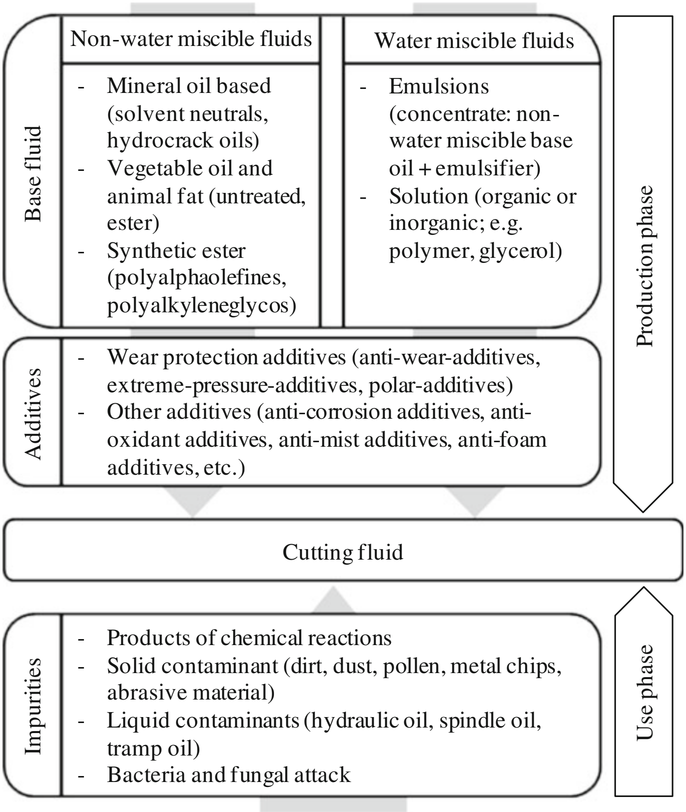

Fig. 2.7 Composition of cutting fluids [according to (DIN 51385 2013, p. 4; Brinksmeier et al. 1999, p. 583)]

The aforementioned base fluids and additives are formulated and mixed for the cutting fluid production according to the required fluid characteristics. However, these characteristics are altered during the utilisation of the cutting fluid, as a result of the demand of additives by the process and the contamination by impurities. These impurities are products of chemical reactions. Examples are the reactions of additives with the workpiece surface during the machining process, detergents adhering to the workpiece or tool surface as well as bacterial or fungal attacks. Further impurities are solid contaminants: this includes produced metal chips and abrasive materials, particles from the environment (dirt, dust, pollen, etc.) as well as organic substances (conglomerates of bacterial colonies and fungal infestations) and liquid contaminants from previous processes (cutting fluid, liquid detergents) or from the machine system (hydraulic oil, slideway oil, etc.) (VDI 3397-2 2007, p. 1ff.; Mang and Dresel 2007, p. 476). A consequence of contamination by these impurities is a change in the original characteristics of the cutting fluid and a reduction of the operating lifetime.

The selection of the cutting fluid depends on tool material, workpiece material, the machining process and process parameters (Vits 1985, p. 95; VDI 3397-1 2007, p. 8f.). According to Vits, the application of non-water miscible cutting fluids in rough grinding processes leads to higher productivity and better surface finishes in comparison with water miscible fluids. In the case of finish grinding, the application of water miscible cutting fluids leads to better results (Vits 1985, p. 95).

In 2013, about 44,800 tons of mineral oil were used to replace or to refill existing cutting fluids in machining processes in Germany. Around 61 % of the total amount were used for non-water miscible cutting fluids. The remaining 39 % were utilised to produce mineral oil-based emulsions (BAFA 2014). Assuming a mineral oil concentration of 5 % (Möller and Nassar 2002, p. 569) led to the production of around 351,500 tons of mineral oil-based emulsion. With an average additive concentration of circa 10 %, around 4,480 tons of additives were needed during the production of cutting fluids.

Procurement prices for cutting fluids range between 3 and 8 €/kg, depending on their formulation with additives, their type and order volume. Considering an average price of 5 €/kg, the sales volume of non-water miscible cutting fluids in Germany is around 136.2 million Euros while that of water miscible cutting fluids is around 87.8 million Euros (year 2013). The total sales volume for mineral oil-based non-water miscible and water miscible cooling lubricants was roughly 805 million Euros in 2008 in the EU27 (Schischke et al. 2012a, p. 6), which amounts to about 161,000 tons of mineral oil-based cutting fluids. These numbers indicate the high economic relevance of the mineral oil-based cutting fluid market.

2.1.3 Grinding System

The grinding system is composed of the grinding machine and its supporting systems. The supporting systems include either a cutting fluid filter or an exhaust air filter (Fig. 2.8). Each of these systems is composed of further subsystems and components, which are described in the next sections.

2.1.3.1 Grinding Machine

Machine tools can generally be defined as energy input dependent stationary systems consisting of linked components, whose professional application results in a product of defined and reproducible geometry (Schischke 2012b, p. 29). The components of a machine tool can be classified into the following items: a machine frame, guides, drives and control units (Tönshoff 1995, p. 16). According to DIN 69651, a grinding machine is a type of machine tool for processes with geometrically undefined cutting edges within the classification of systems for the separation of metal (DIN 69651 1981, p. 3). The design of the grinding machine depends on the grinding process and on the geometry of the machined workpiece,

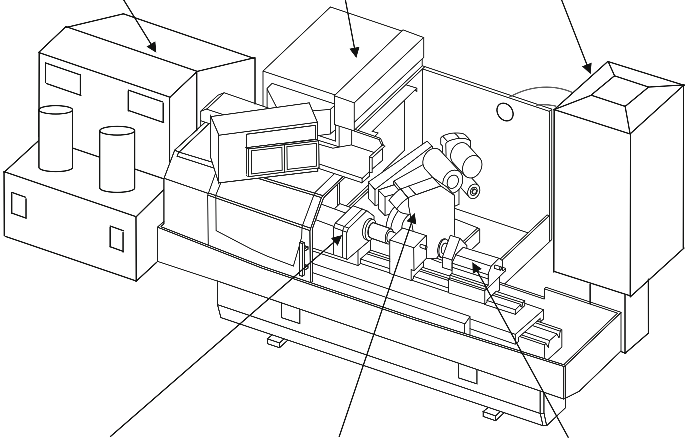

Fig. 2.8 Composition of the grinding system

respectively. Machine types can therefore be classified according to the contact area between workpiece and grinding wheel (peripheral grinding and lateral grinding) or the relative direction of the cutting motion to the main feed motion (down, up, pendular grinding) (Weck and Brecher 2005, p. 219f.).

Around 750.000 CNC machine tools for metal removal processes are installed in the EU27. The distribution of the main types of machine tools (milling machines, turning machines, grinding machines and other cutting machines) is presented in Fig. 2.9. In 2009, the grinding machines had a share of approximately 28 % and represent the second largest group after machining centres (40 %) and before turning machines (23 %) (Schischke et al. 2012c, p. 12ff.). A forecast from Schischke et al. indicates that until 2025 the share of grinding machines will decrease and rank in third place after machining centres and turning machines (Schischke et al. 2012c, p. 12ff.).

2.1.3.2 Cutting Fluid Filter

The cutting fluid filter is an important component in maintaining cutting fluid quality by separating the aforementioned (Fig. 2.7) solid and liquid contaminants from the fluid (VDI 3397-2 2007, p. 2ff.). The process for the separation of these solids can be achieved with five methods: sedimentation, centrifugation, filtration, flotation and magnetic separation (VDI 3397-2 2007, p. 19), while the separation of liquid contaminants can be achieved through skimming, suction, coalescence, flotation and centrifugation (VDI 3397-2 2007, p. 33). During the grinding process,

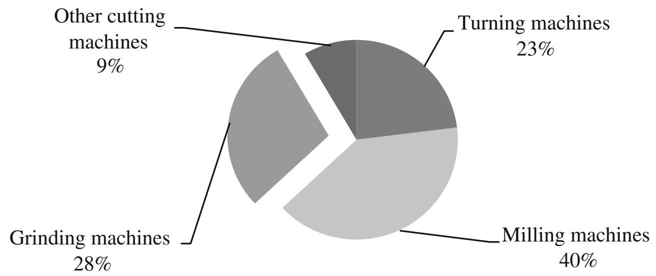

Fig. 2.9 Share of installed CNC machine tools in the EU27 [based on (Schischke et al. 2012c, p. 12ff.)]

the clean cutting fluid is pumped under pressure from a storage tank via the cutting fluid nozzle into the contact zone. After the application the fluid flows back into the cutting fluid filter, is filtered and, if necessary, cooled.

The filter design differs in regard to tank size, number and size of pumps, design of the separation process and the necessity and size of a cooling unit. Furthermore, the grinding process, the number of connected grinding machines and the physical characteristics of the cutting fluid as well as the required fluid purity all have an influence on the cutting fluid filter design (Sutherland 2008, p. 278; VDI 3397-2 2007, p. 18ff.; Silliman 1992, p. 131f.).

Different types of filtration materials, featuring a wet-laid (paper), non-woven and woven structure, can be applied (Sutherland 2008, p. 209ff.). The choice of filtration material depends on the chip size, the cutting fluid type, the cutting fluid filtration principle and the workpiece material. Paper filtration media, for instance, can be applied in a filter cartridge to filter non-water miscible cutting fluids; non-woven filtration material can be used in flat band filtration of water and non-water miscible fluids.

2.1.3.3 Exhaust Air Filtration System

Throughout the grinding process, cutting fluid mist droplets and vapours occur. The mist droplets are between 0.1 and 50 µm (DGUV 2012, p. 20) in size and are mechanically created due to turbulences when the fluid is charged with pressure on the fast rotating grinding wheel and workpiece surface. The cutting fluid vapours are created thermally through the evaporation and incineration of the fluid at high process temperatures. Without the grinding machine encasement and the application of an exhaust air filtration system, the cutting fluid mist droplets and vapours would contaminate the area around the grinding machine and pose a risk to the health of workers and the integrity of the equipment (DGUV 2012, p. 17ff.; BGIA 2006, p. 9ff.).

Exhaust air filters can be divided, according to their filtration concept, into filtering precipitators (about 37 %), electrostatic precipitators (about 50 %), wet precipitators (about 1.5 %), centrifugal precipitators (about 6.0 %) and other precipitators (about 5.5 %). The aforementioned percentages represent the share of different filtration systems used in Germany in 1991 (BGIA 2006, p. 10). Every encapsulated grinding machine is usually connected to a centralised or decentralised exhaust air filtration system. Centralised exhaust air filtration systems filter the exhaust air of multiple machine tools, while the decentralised filtration system is connected to one machine tool.

2.1.4 Energy, Resource and Information Flows of the Grinding Process and System

The grinding process in a grinding system is connected with the demand and transformation of energy, resource and information flows (Fig. 2.10). The input energy flows include the demand and transformation of electrical energy (e.g. powering of the grinding system, realisation of the grinding process), of compressed air (e.g. sealing air inside the tool spindles, workpiece clamping) and of thermal energy (e.g. to cool the spindle or electrical cabinet). Due to the transformation process of energy flows, sonic and vibration emissions as well as thermal emissions from the grinding process and system are created and emitted into the grinding system's environment.

The input resource flows include the unfinished workpiece, the grinding wheel, the conditioning unit and the cutting fluid. The unfinished workpiece is transformed through the application of the aforementioned energy flows into the finished workpiece. In addition to the workpiece, the output resource flows include the chips and tool wear products as well as the grinding wheel and the cutting fluid. The latter ones are only lost for minor proportion and they can be reused as an input resource flow until the end of their service life is reached (Eckebrecht 2000, p. 20f.).

Figure 2.10 shows, besides the energy and resource flows, a third one with the information flows. This flow influences and characterises the relationship between the grinding process and the system. The input information flow includes parameters and state conditions. Among the parameters are the aforementioned geometric and kinematic relationships between the grinding and the conditioning processes, as well as those pertaining to the supply and extraction of the cutting fluid and exhaust air. The state conditions define the characteristics of workpiece, cutting fluid, grinding wheel, conditioning unit, grinding system and supporting units.

The output information flow on the right side encompasses economic, environmental and technological indicators. The economic indicator characterises the cost of the grinding process and system (Eckebrecht 2000, p. 73 ff.; Dettmer 2006, p. 163ff.; Winter et al. 2014, p. 645ff.). The environmental indicators are related to the environmental footprint of the grinding process and system (Dettmer 2006, p. 99ff.; Winter et al. 2014, p. 645ff.). The technological indicators specify the state

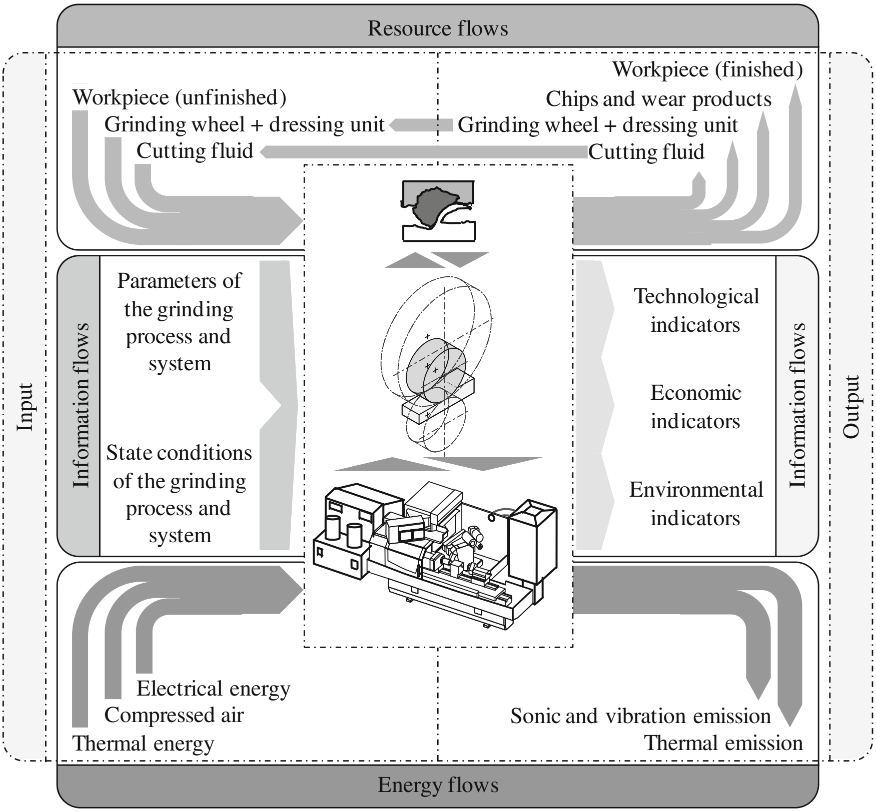

Fig. 2.10 Energy, information and resource flows of the grinding system [based on (Brinksmeier and Schneider 1993, p. 19.06; Winter et al. 2014, p. 645)]

of the ground workpiece (accuracy, surface roughness, material properties, etc.) and the cutting fluid as well as the conditions of the grinding wheel (Rowe 2009, p. 2f.; Winter et al. 2014, p. 645ff.).

The input information flow influences the grinding process and system in the centre. The chosen input information and its achievement potential influences and determines process and system, while the process and system in turn influences the output information flow on the right side in Fig. 2.10. Therefore, changes in the technological, economic and environmental indicators can be achieved by modifying the input information. The range of input information, however, is constrained by limits in the technological, economic and environmental indicators (Winter et al. 2014, p. 645). Furthermore, the indicators partially contradict each other. An increase in cutting depth, for instance, leads to an overall reduction in carbon dioxide emission and costs but also results in an inferior surface quality (Winter et al. 2014, p. 652).

2.2 Modelling of the Grinding Process and System

Energy and resource flow models can be used to describe the interrelations between the various flows presented in Fig. 2.10. Additionally, these models can be used in a control loop to investigate the influence of parameter and state condition variations on the technological, economic and environmental indicators (Fig. 2.11). The application of a control loop is inspired by Baetge, who presented the idea of transferring of the control loop found in control theory to the management of a company (Baetge 1974, p. 30). Baetge considered management as a control element and the real process and system as the controlled system. Thus, a modelled system can be used instead of a real one, as shown in Fig. 2.11. The target value (w) of a specific indicator is defined by the executive management within the control loop. Based on this target value, the designer of the process and system (or operator) develops a strategy with defined process and system parameters and state conditions (u). The strategy is implemented in the theoretical model of the indicator taking into account the boundary conditions of the process and system. The actual value (y) created, however, can be influenced by a disturbance value (z). Therefore, the actual value is transferred back in a feedback loop to determine the deviation using a measuring element. Based on this evaluation, a control deviation or offset (q) is used to create a corrected target value $((f)$ which is used as an input for the control element.

Suitable models and modelling approaches are needed to describe the peculiarities of real processes and systems. The next section will present corresponding approaches and models to predict environmental, economic and technological indicators while considering influencing variables as well as spatial and temporal constraints.

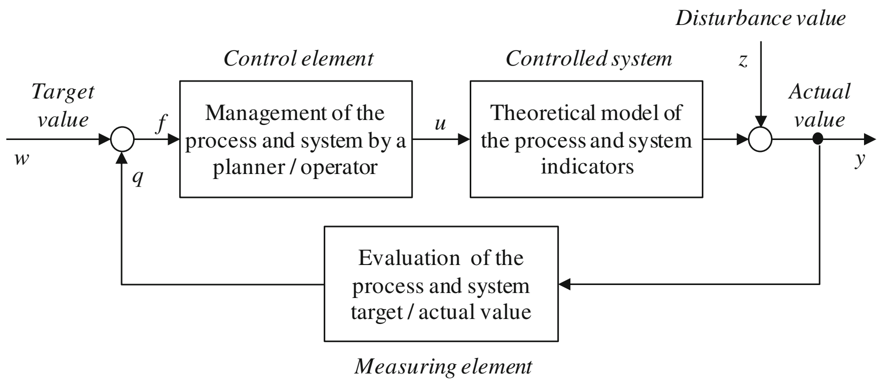

Fig. 2.11 Application of control loop idea to investigate variations of a modelled process and system [based on (Baetge 1974, p. 30)]

2.2.1 Models and Modelling Approaches

The term model can be described as the abstract representation of a process or system, which serves to link causes and effects. It is a mean to reduce the complexity of a process or system to foster understanding and solving (Tönshoff et al. 1992, p. 677; Velten 2009, p. 3). The term possesses three main characteristics: (1) a model is a reproduction of a natural or artificial original; (2) models do not represent all attributes of the original but only those attributes that are relevant to the model creator and/or user; and (3) models are not explicitly associated with their originals (Stachowiak 1973, p. 131ff.).

Different types of models can be distinguished. In case of a model describing a technical system and its relationships, mathematical models can be used. According to Isermann, mathematical models can be derived using a physical or an empirical process analysis (Fig. 2.12) (Isermann 1974, p. 1174). In Fig. 2.12, both types of process analyses are presented. The approach used to derive physical models is presented on the left side, while on the right side is the approach used to derive empirical models.

The physical modelling approach starts with reducing the complexity of the investigated system through the deduction of assumptions for simplification. In the next step, basic equations are derived based on the description of balance equations, physical–chemical relationships, phenomenological equations or entropy balance equations. This set of basic equations of ordinary, partial differential and algebraic equations needs to be solved to derive a first physical model. If the resulting physical model is too complex, it needs to be simplified. A viable option in this context is the reduction of parameters, achieved through the linearisation of equations or by the reduction of the model order (Isermann 1974, p. 1174). Examples of physical models are fundamental analytical models, geometrical kinematic models or models based on molecular dynamics.

The approach used to derive an empirical model is presented in Fig. 2.12 (right side). Experiments are conducted taking into account a priori knowledge about the process (based on a known or unknown structure). During the experiments, the input values as well as the output values are measured. In an identification step, the system relationships are represented as parametric or non-parametric models, depending on whether a model structure can be determined or not. These steps result in an empirical mathematical model (Isermann 1974, p. 1147f.). Examples of empirical models are linear or nonlinear regression models, neural networks and fuzzy logic-based models. Figure 2.12 includes a comparison of physical and empirical modelling. This step can only be carried out if the investigated system is physically and empirically modelled.

Based on the aforementioned comparison, the deviation (difference) between models can be calculated and used to improve each model. Both modelling approaches are an iterative process and the selection of either modelling approach depends on the investigated system. The different characteristics of the empirical and physical modelling approaches are presented in Table 2.1.

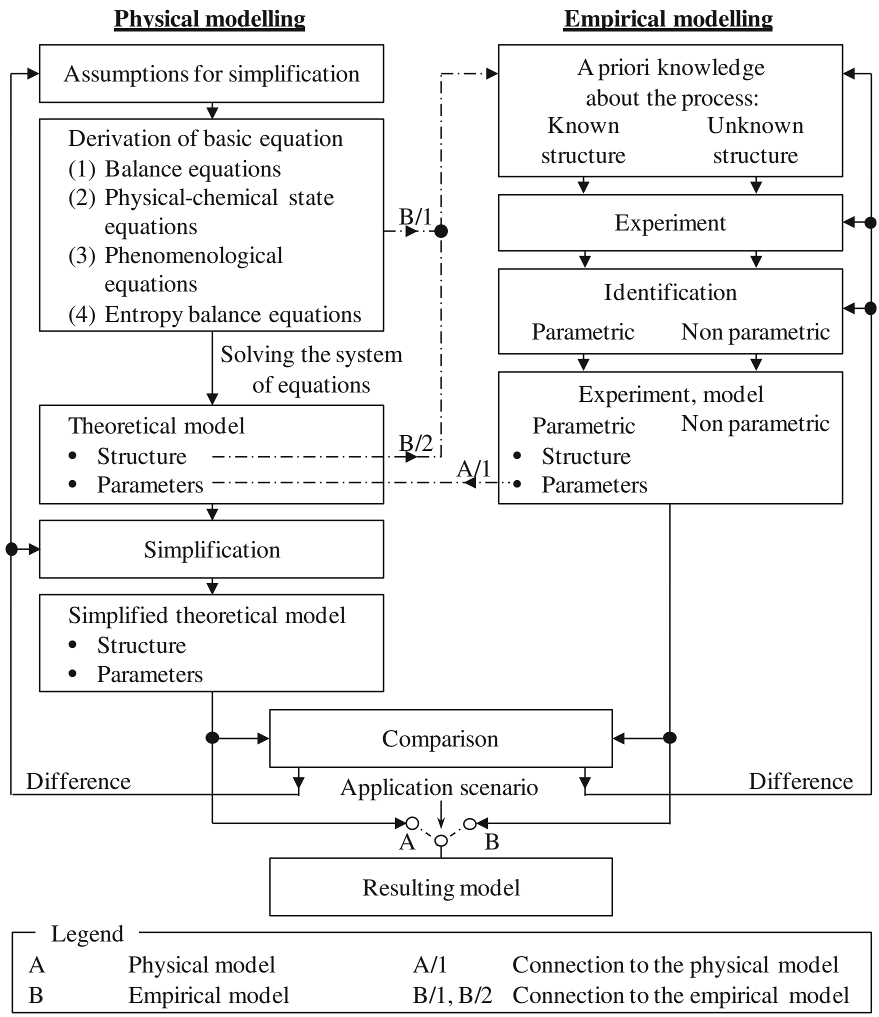

Fig. 2.12 General approach in physical and empirical modelling [according (Isermann 1974, p. 1147)]

The advantage of an empirical approach, in comparison with a physical model, is the precise description of the current system behaviour and a reduced modelling and calculation effort, especially for complex systems. In case of a physical model, all relationships need to be known and mathematically describable. The requirements needed for modelling, calculation and hardware are significantly higher in physical modelling. Furthermore, not all physical relationships are known, and only a limited number of models are available (Knop 1989, p. 18). A disadvantage of the empirical approach, however, is its dependence on experimental data. Therefore, the derived empirical models can only be used for the system being investigated,

Table 2.1 Characteristics of the empirical and physical modelling approaches [based on (Knop 1989, p. 18; Isermann 1974, p. 1148)]

Approach	Physical modelling	Empirical modelling
Characteristics	• Independent from experimental data	• Dependent on experimental data
	• Physical relationships partially unknown, model availability limited	• Limited validity of the model values; yet, very precise description
	• High development and experimental effort before application	• Low development and experimental effort before application
	• High hardware performance necessary	• Low hardware performance necessary
	• If ready for use, then no experiments necessary	• Quick alteration possible, but limited to process
	• Application in science and research	• Application in industrial practice

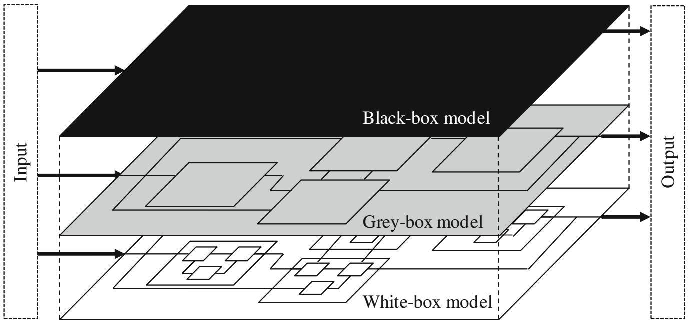

Fig. 2.13 *Black*-box, *grey*-box or *white*-box models

while physical models are case-independent. To overcome these challenges, both modelling approaches can be combined in order to increase the accuracy while reducing the effort (Isermann 1974, p. 1148). The connection is presented in Fig. 2.12 (arrows A/1, B/1 and B/2).

Physical and empirical modelling can be achieved on different levels of aggregation. The level of aggregation can differ between a black-box model, a grey-box model and a white-box model (Fig. 2.13). The black-box model only considers input and output flows entering the investigated system. The system itself, however, is not considered. The white-box-model, on the other hand, takes into account both the flows and all processes and relationships inside the investigated system. The grey-box model is located between the black-box and the white-box models (Haase 2012, p. 27). However, it is difficult to derive a complete white-box model of the investigated system, due to restrictions into the availability of time and data.

Therefore, the derived model can partly have different levels of aggregation (Dettmer 2006, p. 116).

2.2.2 Spatial and Temporal Dimensions in Modelling

The modelling of a system comprises a spatial and a temporal dimension. The spatial dimension (introduced in Sect. 2.1.) includes three hierarchical levels of grinding (chip formation, grinding process and grinding system) and their interrelation. These interrelations are the energy and resource flows between the subsystems or levels. Modelling of these relationships can be realised using empirical or physical equations. The temporal dimension can be represented based on the system's life phases to consider its change as well as influence over the time. Accordingly, temporal modelling needs to take into account the energy and resource flows of the different life phases of the included systems, subsystems, components and elements. The spatial dimension is part of one phase of the temporal dimension, but not vice versa. The different life cycle phases are discussed in more detail in the next section.

Life phases are at the core of life cycle concepts (Herrmann 2010, p. 63). The purpose of these concepts is to represent the time dependence of events and to identify particular phases, based on the trend of relevant properties. The analysis, description or evaluation of each of these phases needs auxiliary methods, tools or organisational measures. Three concept types can be distinguished: the flow-oriented life phase concept, the state-oriented life cycle concept and a phase and state-oriented integrated life cycle concept. Each of these concepts can be linked to environmental, biological, technological and socio-technological systems (Herrmann 2010, p. 63).

The flow-oriented life phase concept can be applied to modelling technological systems. This concept illustrates the interrelation of energy and material throughout the life phases of a system (Herrmann 2010, p. 64). The concept can be further divided into a linear and a cyclical life phase as shown in Fig. 2.14.

The linear concept encompasses the following product life phases: raw material extraction, material production, product production, utilisation and disposal. The concept is based on the factual and consequential sequence of the life phases. Every product-related activity can be assigned to a phase (Mateika 2005, p. 11f.). The cyclical concept additionally includes the reutilisation of the product and components as well as physical recycling and natural recycling. As a result, there is a focus on the material and energy flows instead of the product. The concept describes the recycling and reutilisation of materials and energy (Mateika 2005, p. 11f.). The differentiation of physical and natural world allows for the consideration of material and energy flows between both worlds. The figure also shows different temporal modelling dimensions: cradle to grave, cradle to gate, gate to gate and cradle to cradle (Herrmann 2010, p. 64f.).

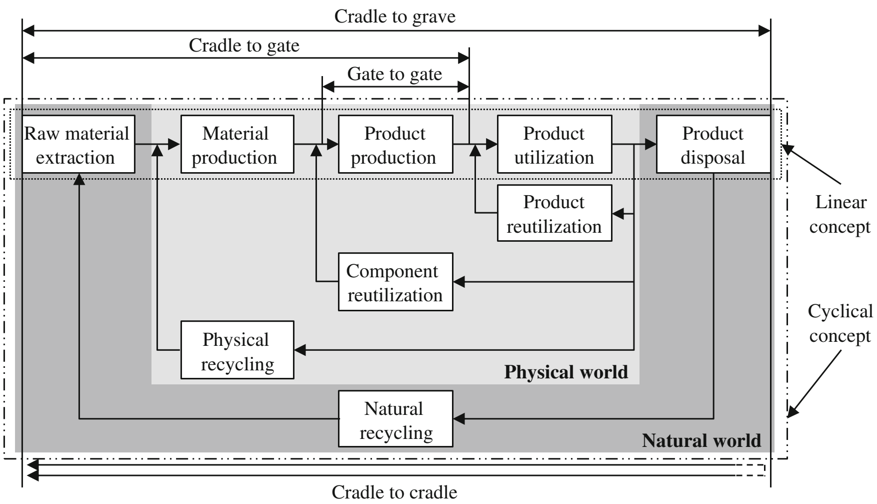

Fig. 2.14 Linear and cyclical product life phase concepts [based on (Herrmann 2010, p. 65)]

Further information on the linear product life phase concept can be found in Senti as well as Stratmann (Senti 1994, p. 10ff.; Stratmann 2001, p. 29ff.) while information on the cyclical product life phase concept can be found in Leber as well as VDI 2243-1 (Leber 1995, p. 45ff.; VDI 2243-1 2002, p. 1ff.).

2.2.3 Modelling of Environmental, Economic and Technological Indicators

The technological, economic and environmental indicators presented in Fig. 2.10 can be used to predict the impact of the grinding process and system on the latter indicators. The prediction of an indicator requires the modelling of such indicator. The following paragraphs will introduce modelling approaches to predict environmental, economic and technological indicators.

The **environmental indicators** can be used to characterise the environmental impact due to energy and resource demand and transformation. The impact can be assessed using the life cycle assessment (LCA) approach found in DIN EN ISO 14040 and 14044. The LCA approach entails the "compilation and evaluation of the inputs, outputs and the potential environmental impacts of a product system throughout its life cycle" (DIN EN ISO 14040 2009, p. 7). The approach comprises four steps: goal and scope definition, inventory analysis, impact assessment and interpretation (DIN EN ISO 14040 2009, p. 17ff.). Due to their iterative nature, it is not necessary to perform the steps in the aforementioned order (Herrmann 2010, p. 153).

The essential contents of the assessment are defined in the goal and scope definition. This includes the specification of system boundaries and functional unit as well as the reason and aim of the study (DIN EN ISO 14040 2009, p. 17; Herrmann 2010, p. 153). The system boundary definition enfolds a spatial and temporal characterisation of the item under investigation as well as a specification of the investigated life phases. Furthermore, an explanation is needed when specific elements of the investigated system and environmental impact categories are excluded from the assessment due to an intended effort reduction (Dettmer 2006, p. 115). The life cycle inventory analysis includes data collection and calculation approaches to determine the relevant input and output flows in the investigated system (DIN EN ISO 14040 2009, p. 25). The analysis is performed on a scientific-technical basis and forms the foundation of the impact assessment. The collected data of the unit process can be classified into energy and resource flows, created products, co-products and waste as well as air emissions and discharges to water and soil (DIN EN ISO 14040 2009, p. 26). In the next step, the life cycle impact assessment is conducted by associating inventory data with specific environmental impact categories and category indicators (DIN EN ISO 14040 2009, p. 27). In addition to selecting impact categories, category indicators and characterisation models, the life cycle impact assessment imperatively includes a classification step as well as a characterisation step (DIN EN ISO 14040 2009, p. 30). In addition to the direct effects, determined via impact categories, indirect effects are also considered, such as health risks due to environmental damages (Herrmann 2010, p. 155). During the interpretation phase, the results of the assessment of the life cycle impact are analysed, evaluated and completed according to previously defined goals and the scope of the investigation (Dettmer 2006, p. 119). For the presentation of the interpreted results, verbal-argumentative, one- or multi-dimensional approaches and methods can be used, such as cumulated energy demand, ECO-Indicator ’99, material input per service unit, CML-method (Herrmann 2010, p. 156–163).

The application of the LCA methodology in the modelling and evaluation of the environmental impact of grinding processes and systems was investigated by various authors. The focus on modelling and evaluation varied depending on the investigated element of the grinding process and system. For example, Hansen et al. and Dettmer modelled and evaluated the impact of mineral oil-based cutting fluids in comparison with cutting fluids based upon animal fats and vegetable oil in grinding (Hansen et al. 2005, p. 3ff., Dettmer 2006, p. 99ff.). Furthermore, Dettmer investigated the environmental impact of treatment strategies in the recycling of grinding swarf mixed with different cutting fluid using an LCA (Dettmer 2006, p. 147ff.). In a simplified LCA, Kirsch et al. determined the environmental impact of a vitrified bonded aluminium oxide grinding wheel based on energy demand (Kirsch et al. 2014, p. 74ff.). Linke and Overcash presented a selective overview of the energy and material flows of a grinding process and system and showed options to represent these flows using simplified formulations (Linke and Overcash 2012, p. 293ff.). Murray et al. as well as Winter et al. conducted a simplified LCA of a grinding process and system considering the environmental impact resulting from electrical energy demand, grinding wheel and cutting fluid (Murray et al. 2012,

p. 1604ff.; Winter et al. 2014, p. 644ff.). Dettmer observed a prevalent use of the LCA methodology in research and a minor, but growing, application in industry and politics. The reason for this difference is explained by Dettmer; it is due to the relatively high costs of the assessment in terms of time and money, which affect the realisation of a LCA (Dettmer 2006, p. 120f.).

The created costs and revenues connected with the investigated process and system fall within the **economic indicators**. The costs can be determined through the application of conventional cost accounting (CCA), material flow cost accounting (MFCA) and life cycle costing (LCC).

CCA is part of the internal accounting of companies. Its objective is to provide well-grounded information about the demand of material and about good or service creation, as both are needed to support internal decision-making (Herrmann 2010, p. 136). The CCA can be further divided into cost-type accounting, cost-centre accounting and cost-unit accounting. The approach considers the relationship of time and cost, based on the focus on the past or the future. According to each focus, total absorption costing or incremental costing can be applied (Herrmann 2010, p. 136). Total absorption costing includes the full costs for product or service creation. It rests on the assumption that all costs of a company can be directly assigned. Within incremental costing, only a selected share of the overall cost is directly assigned, while the remaining share is considered as additional overhead cost (Becker et al. 2011, p. 229/251; Herrmann 2010, p. 136). Incremental costing is usually applied in companies, because the underlying organisational structure, including central services (e.g. technical building services), constrains the source-related assignment of costs to a product or service. Costs related to energy, auxiliary and residual materials are allocated as overhead costs and not as specific product or service costs (Schlosser 2013, p. 28). If a critical level is exceeded, the overall operating overhead cost might be beyond control (Schlosser 2013, p. 28).

The MFCA approach, standardised in DIN EN ISO 14051, is a “tool for quantifying the flows and stocks of materials in processes or production lines in both physical and monetary units” (DIN EN ISO 14051 2011, p. 15). Its objective is to enhance the economic and environmental performance of a process thanks to improved material and energy use. The approach allows the identification of production costs and their allocation to the created residual materials. Increasing the transparency of material as well as the energy flows and the transparency of associated costs of products and waste is therefore the main focus of such approach. This transparency allows the calculation of economic saving potential, the identification of hidden costs related to material losses and the prediction of productivity increase, if material losses are prevented (Schmidt 2011, p. 2). Fundamental elements of the MFCA are the quantity centre and the material balance. The quantity centre represents a process or a part of a process. The inputs and outputs of this process are quantified in physical and monetary units. Therefore, the quantity centre serves as a basis for data collection on energy and material flows as well as on material, energy, system and waste management costs (DIN EN ISO 14051 2011, p. 19). The material balance compares the quantity centre’s input and outputs to identify missing materials or other gaps in the data. It is based on the assumption that material and energy can neither be destroyed nor created, but only transformed. The application of the MFCA, however, is also connected to restrictions such as the limited consideration of material and recycling loops and the unilateral allocation rule (Viere et al. 2011, p. 652–656).

The LCC approach "…aims at optimising the total costs and yields of a system and of the related activities and processes arising over its life cycle" (VDI 2884 2005, p. 4). Within the aforementioned approach, a supply and demand-oriented perspective can be distinguished (Herrmann 2010, p. 144). The focus of the demand-oriented perspective lies in the determination of costs during the ownership of the investigated element, also called the Total Cost of Ownership. The focus of the supply oriented perspective is on the created revenues or costs in life phases after product sale (Herrmann 2010, p. 144, Dettmer 2006, p. 164). LCC can be achieved either based on approaches suggested by VDI 2884, DIN EN 60300-3-3, VDMA 34160 or in connection with an LCA (Herrmann 2010, p. 145f.; VDI 2884 2005, p. 6ff.; DIN EN 60300-3-3 2014, p. 14; VDMA 34160 2006, p. 2ff.; Dettmer 2006, p. 165). The advantage of the latter option is that the same input and output values can be considered for the calculation of environmental and economic indicators. LCA and LCC are therefore a reliable basis for decision-making (Möller 2000, p. 170).

Various studies have investigated the application of the aforementioned cost models in evaluating the economic impact of grinding processes and systems. For example, Langemeyer as well as Garcia et al., among others, used a simplified CCA to compare different cutting fluid application strategies in surface grinding (flood lubrication with minimal quantity lubrication) (Langemeyer 2002, p. 127ff.; Garcia et al. 2013, p. 106). In combination with a LCA, Dettmer conducted a LCC to compare the impact of a mineral oil-based, a vegetable oil-based and an animal fat-based cutting fluid (Dettmer 2006, p. 162ff.). The LCC methodology was also used by Enparantza et al. to evaluate the economic impact of a grinding process and system (Enparantza et al. 2006, p. 717). A simplified MFCA was conducted by Winter et al. to determine the influence of the cutting fluid type on the economic impact of an internal cylindrical grinding process (Winter et al. 2014, p. 644ff.).

The foundation for the evaluation of environmental and economic indicators is therefore the availability of relevant input and output flows, which can be obtained using an energy and resource flow analysis. Schaltegger and Sturm state that almost every LCA is based on energy and resource flows (Schaltegger and Sturm 2000, p. 65). DIN EN ISO 14051 comes to similar conclusions with regard the costs (DIN EN ISO 14051 2011, p. 19). Thus, the relevant energy and resource flows need to be modelled. For this purpose, the aforementioned physical modelling approach can be used to obtain functions of the input–output relationship. The physical modelling can be realised in an iterative process.

The term **technological indicators** include characteristics, which represent the investigated system or the output of this system with regard to quality as well as energy and resource demand. In case of manufacturing processes, the output is the produced workpiece. The workpiece can be classified according to the achieved quality, such as surface roughness, accuracy and material properties. The demand of

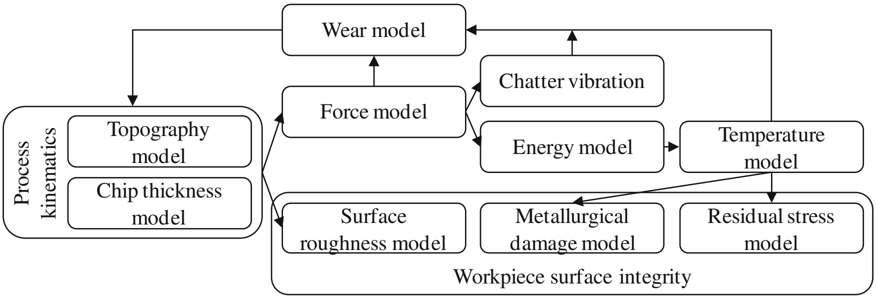

Fig. 2.15 Relationships between physical models in grinding [based on (Brinksmeier et al. 2006, p. 668; Tönshoff et al. 1992, p. 678)]

energy and resources can be classified according to the process and system energy, the wear of the tool or by the forces used during the process. As previously mentioned, the value of each technological indicator depends on the selected input variables. These relationships can be either physically or empirically modelled.

For the physical modelling of the grinding process, the knowledge of the interaction between abrasive grain and workpiece is essential, due to its influence on material impact and the removal process (Brinksmeier et al. 2006, p. 668). Tönshoff et al. (1992, p. 678) and Brinksmeier et al. (2006, p. 668) produced a comprehensive review of the interactions described in the literature and described the relationship between physical models in grinding presented in Fig. 2.15.

The foundation of physical modelling is the knowledge about grinding process kinematics, in the form of grinding wheel topography and chip thickness. The grinding wheel topography model characterises active grain distribution and concentration. Both influence the individual and combined abrasive grain–workpiece interaction and, as a result, the chip formation process or chip thickness. With knowledge about grinding process kinematics, process forces and the achieved workpiece surface roughness can be modelled. A grinding energy model and a wear model can be produced on the basis of the forces. The energy model can be used to derive temperature models for the tribological partner. The temperature model serves as an input for metallurgical damage (e.g. grinding burn) and residual stress modelling. Surface roughness, metallurgical damage and residual stress characterise the surface integrity. The temperature has further impact on the grinding wheel wear model. The wear model itself has an impact on process kinematics, due to the wear of the abrasive grains which change the grinding wheel topography and, as a result, process kinematics.

As defined in Sect. 2.1, the grinding process is characterised by its statistically disorderly located single cutting edge engagement with the workpiece surface. This engagement process needs to be included in process kinematics modelling. Furthermore, the process parameters, such as cutting depth, speeds, feeds, influence the kinematics as well. In addition to the stochastic wheel topography, process kinematic models also need to cover process and time-dependent changes of the grit characteristics (Brinksmeier et al. 2006, p. 668). Thus, physical modelling needs a lot of input information to represent the grinding process. Furthermore, this information needs to be up to date to reflect the stochastic, dynamic and time-dependent nature of the grinding process. The following sections will present modelling approaches used to predict grinding force and energy, temperature, workpiece surface integrity and wear.

Grinding Force and Energy Modelling

The modelling of grinding forces and energies can be conducted on the basis of different approaches (Challen and Oxley 1979, p. 299ff.; Chen 1995, p. 1ff.; Xie and Williams 1996, p. 21ff.; Hou and Komanduri 2003, p. 1579ff.). Challen and Oxley modelled possible interactions of a single hard wedge with a perfectly rigid plastic solid in a two-dimensional approach based on slip-line fields (Challen and Oxley 1979, p. 299 ff.). Using a three-dimensional approach, Xie and Williams describe the interaction between a single and hard pyramid-shaped asperity with a softer surface (Xie and Williams 1996, p. 21ff.). Both approaches are initially proposed in the modelling of wear and friction between two partners in contact and only indirectly focus on force modelling. Badger and Torrance, however, adapted and modified the approaches according to the requirements of the grinding process. Thus, the authors compared both models for the formulation of grinding forces and concluded that the three-dimensional approach leads to more accurate results than the two-dimensional approach (Badger and Torrance 2000, p. 1110f.). In a further investigation, the authors extended the approach and considered the effects of the conditioning process (Torrance and Badger 2000, p. 1787ff.). Hou and Komanduri proposed to model the grinding process mechanics based on probability statistics (Hou and Komanduri 2003, p. 1579ff.). The approach was also used by Rabiey to model a dry grinding process (Rabiey 2010, p. 1 ff.). In this investigation, however, the application of probability and statistics led to limited accuracy (Rabiey 2010, p. 96ff.). A further approach, especially in determining the normal ($f_{n,i}$) and tangential ($f_{t,i}$) force per grain of a grinding process, was suggested by Chen and Rowe. The approach was initially proposed by Shaw and then modified by Chen and Rowe (Chen 1995, p. 1; Chen and Rowe 1996, p. 883 ff.). Connected with the grinding forces are chatter vibrations caused, for example, by unbalanced grinding wheels or the interaction of the grinding wheel with the workpiece (Inasaki et al. 2001, p. 516f.). In order to predict chatter vibrations in grinding processes, Altintas and Weck investigated and presented a comprehensive overview of the physical models (Altintas and Weck 2004, p. 619ff.).

Thermal Modelling

Once sufficient knowledge about the grinding forces and power has been obtained, the workpiece temperature can be modelled. A common reference for most physical temperature models in grinding are the works of Carslaw and Jaeger on a moving heat source (Jaeger 1942, p. 203ff.; Carslaw and Jaeger 2004, p. 1ff). Outwater and

Shaw were the first to apply this model for the thermal analysis of a grinding process. The model was further developed by Hahn, because of the inclusion of the heat source created by the grain wear flat. Takazawa simplified the approach by presenting an approximation equation while DesRuisseaux as well as Zerkle incorporated the impact of the cutting fluid (Brinksmeier et al. 2006, p. 669). A comprehensive model, which takes into account the heat flows into tool, workpiece, cutting fluid and chips, was independently presented by Rowe, Lavine or Malkin and Guo (Rowe 2009, p. 365ff.; Lavine 2000, p. 4447ff.; Malkin and Gou 2008, p. 157ff.).

Workpiece Surface Integrity Modelling

Workpiece surface integrity can be described based on surface roughness, metallurgical damage and residual stress (Comley 2005, p. 24). At the core of physical surface roughness modelling is the assumption that the workpiece surface is created due to the interaction between a hard and sharp asperity and a softer workpiece material (De Vathaire et al. 1981, p. 55ff.; Gilormini and Felder 1983, p. 195ff.). On the basis of this assumption, several authors have described the workpiece surface roughness created by a grinding process based on a similar physical model (Chen and Rowe 1996, p. 883; Torrance and Badger 2000, p. 1787ff.; Nguyen and Butler 2005, p. 1329ff.; Baseri et al. 2008, p. 1091ff.). The approaches differ with regard to the assumed grain shape [sphere shape (Chen and Rowe 1996, p. 883; Nguyen and Butler 2005, p. 1329ff.; Baseri et al. 2008, p. 1091ff.) and triangular shape (Torrance and Badger 2000, p. 1787ff.)]. Rapid cooling and heating during a grinding process can result in residual stress due to phase transformation and thermoplastic deformation of the workpiece material. Connected with the thermally induced residual stress is metallurgical workpiece damage. The term describes changes in micro-hardness and structure, due to thermally induced micro-cracks, fatigue strength or reaustenitisation. The physical modelling of these two processes was investigated by several authors using computer-related algorithms or simulations (Field and Koster 1978, p. 523ff.; Vansevenant 1987, p. 1ff.; Mahdi and Zhang 1998, p. 1289ff.; Moulik et al. 2001, p. 831ff.; Hamdi et al. 2004, p. 277).

Wear Modelling

The superposition of different wear phenomena and mechanisms further complicates physical wear modelling. Meng identified in a literature review of more than 5000 publications (published between 1957 and 1992) about 182 models (Meng 1994, p. 4) to describe the wear process. In this survey, Meng concluded that each investigated model focuses on a different and very small part of the wear process, and no broadly accepted theory exists to fully explain the wear mechanism and phenomena (Meng 1994, p. 79).

Another option, if the physical modelling is complex, inaccurate or time-consuming, is empirical modelling based on a regression analysis of experimental grinding data (Tönshoff et al. 1992, p. 678). Regression analysis describes a functional relationship between the input variables and the output indicators. This relationship usually has an exponential character in grinding and is represented by the general equation shown in (Eq. 2.7) (Knop 1989, p. 25).

$$Y = K_i + C_l \cdot \prod_{i=1}^{n} x_i^{E_i} \tag{2.7}$$

The term Y represents the output indicator and x_i the input variables (usually the process parameters). Each term x_i is quantified by the exponent E_i while the constants K_i and C_j represent the influences that are not explicitly included in the model. An advantage of the exponential model is the representation of a large scope of curved shapes and the determination of the calculated input–output relationship with a small error value, in comparison with the measured values (Knop 1989, p. 26). One of the disadvantages of the equation (Eq. 2.7) is that the description of inflexion points is not possible. This can be of interest if a trend with an opposite behaviour has to be considered, for example time-related influence on the conditioning parameters or grinding parameters (Knop 1989, p. 27). To overcome this drawback, the equation (Eq. 2.7) can be changed to include a superposition of several exponential expressions [see (Eq. 2.8)].

$$Y = K_i + \sum_{l=1}^{m} \left(C_l \cdot \prod_{i=1}^{n} x_i^{E_{li}} \right) \tag{2.8}$$

2.3 Eco-efficiency

2.3.1 Origin of Eco-efficiency

As previously mentioned, the origin of the eco-efficiency approach lies within sustainable development. The sustainable development concept gained an increased importance in the second half of the 20th century. In 1972, Meadows et al. presented the report "The Limits to Growth" which contained a forecast of future development. The report rested on the assumption that the pattern of unsustainable demand and production would have stayed constant for the next decades. The report envisaged a worldwide increased in environmental pollution, depleted natural resources, widespread undernourishment and an increased world population (Meadows et al. 1972, p. 122 ff.). This relationship was also described by Ehrlich and Holdren in (1972). The authors correlated economic development with the created environmental impact and presented the $I = PAT$ equation. The equation relates impact (I) with population (P), affluence (A) and technology (T) (Ehrlich and Holdren 1972, p. 20).

In the following years, this report had a significant influence on the political discussion on sustainability (Herrmann 2010, p. 44). In 1987, a commission under the guidance of Gro Harlem Brundtland presented a first definition of the term sustainable development in the report "Our Common Future". The so-called

Brundtland report defined “sustainable development” as “development that meets the needs of the present without compromising the ability of future generations to meet their own needs” (Brundtland Report 1987, p. 15). In the following years, the concept of sustainable development was widely considered as a goal. As previously mentioned, the concept did not provide any strategies to trigger a change from unsustainable to sustainable development (Mickwitz et al. 2005, p. 1603).

A corresponding approach was first introduced in 1989 by Schaltegger and Sturm through the use of the “eco-efficiency” approach as a means to sustainable development (Schaltegger and Sturm 1989, p. 15ff.). The approach is based on the idea of creating more value for goods and services while creating less waste and pollution. However, it was not until 1992, following the United Nations Conference on Environment and Development held in Rio de Janeiro (also called the “Earth Summit”), that the term became widely published. Prior to the summit, Schmidheiny published the “Changing Course” report as an input to the summit of the Business Council of Sustainable Development (Jollandy 2003, p. 1). The term eco-efficiency was coined with this report (Schmidheiny 1992, 9ff.) and due to its background later described as the “business contribution to sustainable development” (OECD 1998, p. 15). A further achievement of the summit was the “Agenda 21”, which proposed suggestions for national policies and strategies to encourage changes in unsustainable demand patterns. Paragraph 4.15 specifies that the achievement of “… the goals of environmental quality and sustainable development will require efficiency in production and changes in consumption patterns to emphasise optimization of resource use and minimization of waste” (UN 1992, p. 20). Therewith, business and politics defined “efficiency” and “sufficiency” as sustainable development strategies in order to separate industrial growth from environmental impact. Both strategies, however, commonly focus only on the improvement of a system, instead of the creation of a new one. To overcome this drawback, a third strategy was introduced: consistency. As previously mentioned, consistency focuses on the reconcilability of economy and environment (Herrmann 2010, p. 51). The consistency strategy is sometimes also labelled with the term eco-effectiveness (Liedtke et al. 2013, p. 1144). According to Schaltegger, the term eco-effectiveness indicates the degree of absolute environmental compatibility of a business activity (Schaltegger 1999, p. 12).

2.3.2 *Definition of the Term Eco-efficiency*

Eco-efficiency can be defined as a “ratio of some measure of economic value added to some measure of environmental impact. The higher the value added, the more efficient is the use of environmental services” (Ehrenfeld 2005, p. 6). A comprehensive study by Koskela and Vehmas pointed out that there is no commonly agreed or exact definition for the term eco-efficiency (Koskela and Vehmas 2012, p. 547f.). The study further shows that the lack of a common definition is due to different stakeholders using the concept for different purposes, application levels and improvement focuses. As far as the purpose of the application is concerned, the eco-efficiency approach can be used as an assessment method or as a management strategy. Each application level differs according to the political/geographical dimension (regional, national, global), the business dimension (company, corporate, sectoral) and the goods-related dimension (product, service). The improvement focus can be on the productivity increase of the economic value, on the intensity decrease of the environmental impact or on a productivity increase and decrease in intensity at the same time (Koskela and Vehmas 2012, p. 548). From a production perspective, productivity is an absolute measure, defining "the ratio of the output that is produced to the input that it uses" (Coelli et al. 2005, p. 2f.). This definition is sometimes used to define efficiency as well, yet the definitions of productivity and efficiency are not exactly the same. Productivity is an absolute concept based on the ratio of input and output. Efficiency is a relative concept describing the distance between the achieved quantity of input and output, and the optimal quantity of input and output defined by the production frontier (Fried et al. 2008, p. 7f.; Coelli et al. 2005, p. 2f.; Bellgran and Säfsten 2010, p. 260; Daraio and Simar 2007, p. 13f.). In case of eco-efficiency, productivity can be defined as producing more value with less environmental impact. Intensity usually represents the technical performance of a system and is defined as the ratio of produced output per time (Hadeler et al. 2000, p. 1571). In eco-efficiency, intensity can be defined as lowering the environmental impact per created value. Examples of internationally accepted eco-efficiency definitions from governmental and non-governmental organisations are presented in Table 2.2.

Table 2.2 Definition of the term eco-efficiency

World Business Council for Sustainable Development (WBCSD)	"Eco-efficiency is achieved by the delivery of competitively priced goods and services that satisfy human needs and bring quality of life, while progressively reducing ecological impacts and resource intensity throughout the life cycle to a level at least in line with the earth's estimated carrying capacity" (BSCD 1993, p. 9)
Organization for Economic Co-operation and Development (OECD)	"…the efficiency with which ecological resources are used to meet human needs. It can be considered as a ratio of an output divided by an input; the "output" being the value of products and services produced by a firm, a sector or the economy as a whole, and the "input" being the sum of environmental pressure generated by the firm, sector and economy." (OECD 1998, p. 7)
European Environment Agency (EEA)	"A concept and strategy enabling sufficient delinking of the 'use of nature' from economic activity needed to meet human needs (welfare) to allow it to remain within carrying capacities; and to permit equitable access and use of the environment by current and future generations" (EEA 1999, p. 35)
International Standard Organisation (ISO 14045)	"Aspect of sustainability relating the environmental performance of a product system to its product system value" (DIN EN ISO 14045 2012, p. 7)

The first definition in Table 2.2 was formulated in 1993 by the Business Council for Sustainable Development (BCSD) shortly after the Earth Summit. The BCSD merged in 1995 with the World Industry Council for the Environment to form the World Business Council for Sustainable Development (WBSCD). Eco-efficiency can thus be interpreted as a management strategy taking into account the business dimension of a company with a focus on a productivity increase that is inversely proportional to its environmental impact. This definition describes the achievement of the eco-efficiency, when specific economic (competitively priced products) and environmental (earth's estimated carrying capacity) limits are reached (BSCD 1993, p. 9). In 1998, the Organisation for Economic Co-operation and Development (OECD) defined eco-efficiency as a management strategy as well, with a focus on the political/geographical and business dimension. The definition is general and can be interpreted as "more from less"; no limits were specified (OECD 1998, p. 7). The definition formulated by the European Environment Agency (EEA) is a management strategy that can be applied in the political/geographical and business dimensions. The focus is on increasing productivity while lowering the environmental intensity. This is explicitly stated in the passage by describing a "sufficient delinking of the 'use of nature' from economic activity" (EEA 1999, p. 35). Furthermore, a lower limit in regard to the environmental intensity is specified by the carrying capacities of the earth. The last definition in Table 2.2 was published in 2012 by the International Standard Organisation (ISO 14045 and the DIN EN ISO 14045). The definition describes an assessment method to investigate products and services; as a result, there was no specific focus on productivity and intensity (DIN EN ISO 14045 2012, p. 9f.).

2.3.3 Eco-efficiency Assessment Approaches

The assessment of eco-efficiency can be conducted using approaches presented by Saling et al. (2002, p. 203ff.), Rüdenauer et al. (2005, p. 105ff.), Steen et al. (2009, p. 1ff.) or the DIN EN ISO 14045 (2012, p. 1f.). The approach presented in DIN EN ISO 14045 represents an internationally accepted standard, which also considers the works of Saling et al. and Rüdenauer et al. The approach presented in DIN EN ISO 14045 will be described in more detail in the following paragraphs. The eco-efficiency assessment approach described in DIN EN ISO 14045 can be applied to investigate the ratio of some economic values in conjunction with the environmental impact of manufacturing processes and systems. The assessment of eco-efficiency comprises five phases: (1) goal and scope definition, (2) environmental assessment, (3) product system value assessment, (4) quantification of eco-efficiency and (5) interpretation.

The **goal and scope definition** (1) specifies the purpose of eco-efficiency assessment, intended audience and intended use of the results, while the scope definition includes a multiple number of items which are needed to specify the key parts of system boundaries, interpretations and limitations (DIN EN ISO 14045 2012, p. 12f.). The description of system boundaries comprises the characterisation of the product system to be assessed in terms of name, scale, location, time and main stakeholders, as well as the function and functional unit of the product system to provide a reference for environmental and value assessment. Furthermore, the system boundary needs to be specified in accordance with ISO 14044 and has to include the definition of the product system value by the description of the value type (functional, monetary or other), as well as the methods used to determine the value. The characterisation of limitations defines the conditions under which the assessment is made, and constrains it to a specific application scenario (DIN EN ISO 14045 2012, p. 12 ff.).

Based on ISO 14040 and ISO 14044, the aforementioned **environmental assessment** (2) is conducted to determine the potential environmental impact of the product system (DIN EN ISO 14045 2012, p. 16 ff.). The calculation is based on the LCA approach and is defined as the "compilation and evaluation of the inputs, outputs and potential environmental impact of a product system throughout its life cycle" (DIN EN ISO 14045 2012, p. 7). The approach comprises the realisation of four steps: goal and scope definition, inventory analysis, impact assessment and interpretation (DIN EN ISO 14040 2009, p. 17 ff.). Due to the iterative nature during the realisation of the assessment approach, it is not necessary to perform the steps in the aforementioned order.

The **product system value assessment** (3) considers the full life cycle of the product system by assessing the worth or desirability of ascribed functional, monetary or other values. The functional value is defined as a "numerical quantity representing functional performance or desirability of a product system, and is subject to improvement" (DIN EN ISO 14045 2012, p. 17). Therefore, the value needs to be measureable. The monetary value of the product system can be reflected in costs, price, added value, etc. Other values can also be considered. These values are characterised by their intangible nature (e.g. aesthetics, brand, cultural and historical values) and can be determined by means of market research (DIN EN ISO 14045 2012, p. 17f.).

During the **quantification of eco-efficiency** (4), the ratio of the results from environmental assessment and product system value assessment is determined in accordance with goal and scope definition. The resulting equation is presented in (Eq. 2.9) (DIN EN ISO 14045 2012, p. 18f.).

$$\text{Eco-efficiency} = \frac{\text{Product system value}}{\text{Environmental impact}} \tag{2.9}$$

In connection with the quantification of eco-efficiency, a sensitivity and uncertainty analysis should be performed. The influence of data and methodology on the calculated eco-efficiency can be determined through a sensitivity analysis. The uncertainty analysis can provide information regarding the influence of data and assumption uncertainties on the result of the assessment.

In the **interpretation** (5) phase, the results of the eco-efficiency assessment are investigated in accordance with the aim of the assessment. Interpretation concludes the eco-efficiency assessment. This step includes the identification of the significant parameters, the evaluation of completeness, sensitivity, uncertainty and consistency and the formulation of conclusions, limitations and recommendations. Foundation of the interpretation phase is the transparent and well-grounded nature of the results (DIN EN ISO 14045 2012, p. 19f.).

2.4 Preliminary Conclusion

As the previous sections have shown, the task of reducing environmental impact while pursuing economic growth and planning or operating an industrial grinding process and system is a complex challenge. Complexity arises from a versatile environment with many competing demands in terms of technological, economic and environmental indicators. Additionally, there are a multitude of combinations for grinding process parameters and system configurations. A definitive statement regarding the influence of the planned or existing grinding process and system on these indicators is not yet available. Accordingly, there is a need for a suitable approach to support decision-making. Such an approach needs to consider the antagonistic interrelationships among the various indicators and the different grinding process parameters and system configurations, in addition to fostering the reduction of environmental and economic impact.

In the light of the existing evidence and specifications, the following conclusions can be drawn:

- In order to represent decision-making scenarios connected with the planning and operating of an industrial grinding process and system, a generic approach is necessary. The approach needs to consider requirements and peculiarities of grinding systems consisting of different subsystems (e.g. grinding machine, supporting unit), components (e.g. grinding wheel, conditioning unit, cutting fluid) and elements (e.g. pump and spindle drives).
- To conduct a straightforward planning of the system and its operation, knowledge about the available and suitable technological, economic and environmental impact indicators as well as their antagonistic relationship is necessary.
- The operation of grinding processes and systems is connected with different energy and resource flows. Each of these flows can be described using process and system parameters as well as properties. To support the planning and operation of grinding processes and systems, it is necessary to specify the relevant flows as well as parameters and properties.
- In addition to the knowledge of the relevant flows, as well as parameters and properties, it is also necessary to determine their influence on the technological, economic and environmental impact indicators. For this purpose, physical and empirical models can be applied. It is necessary that the formulation of the models is accurate and case-independent.
- Manufacturing companies face an increased demand to reduce environmental impact while staying competitive, a demand driven by the political, social and

economic environment of the company. Accordingly, improvement strategies and options are necessary. In addition to strategies and options, it is necessary to provide an evaluation approach, which includes the interrelationships between technological, economic and environmental impact indicators.

The main question based on these concerns is how to cope with the aforementioned challenges. What support to decision-making is necessary when new grinding processes and systems are planned or an existing one needs to be improved?

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http://www.springer.com/978-3-319-25203-2

Eco-efficiency of Grinding Processes and Systems
Winter, M.
2016, XXVII, 227 p. 92 illus., 86 illus. in color., Hardcover
ISBN: 978-3-319-25203-2