Chapter 2
Energy Demand of Machine Tools and Performance Management

This chapter introduces the thematic context as a basis for the elaboration of the research. First, the ecological implications of industrial growth in the economic system are presented, triggering the initiation of the concept of sustainable development. An analysis of energy flows in production systems is then given to identify the origins of energy demand and extended in detail for machine tools. Based on an assessment of energy improvement measures for machine tools according to the availability and barriers, the implications of imperfect information on improving the energy demand are reflected. As a method for promoting efficiency, performance management is introduced and analysed in terms of the feasibility to determine minimum energy requirements and to guide improvement.

2.1 Implications of Energy Usage in Industry

Economic systems interact with the ecologic system through the exchange of input and output flows. The ecologic system represents the cradle of natural resources for the value creation processes within the economic system and the sink for emissions and waste (Dyckhoff and Souren 2008; Meadows et al. 2001). Resources are generally divided into renewable and non-renewable feedstock. While non-renewable resources like coal, natural gas and mineral oil are limited in availability, renewable sources as organic material can provide a regenerative supply. The consumption of resources and the release of emissions and waste facilitate the growth of the economic system. Especially, energy resources are an indispensable input factor of the economic system for value creation (Singh et al. 1998; Nolte and Oppel 2008).

The world's primary energy demand was about 495 quadrillion Btu in 2007. The industrial sector accounts for more than 50 % of the energy used with more than 249 quadrillion Btu and dominates the commercial, residential and transportation sector. The demand for primary energy in industry is allocated to five energy sources, with electricity taking up the largest share of 37 % (see Fig. 2.1).

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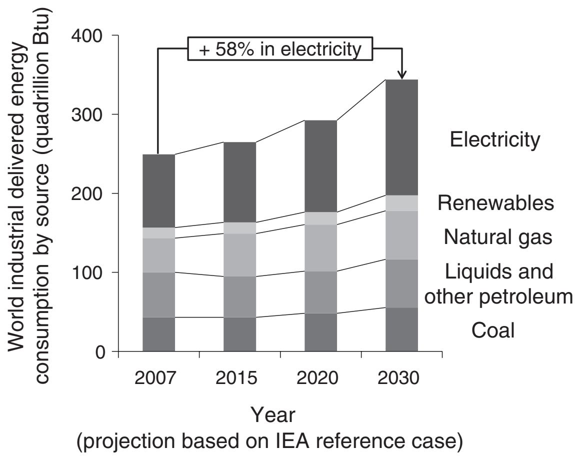


Fig. 2.1 Projection of world industrial energy consumption by sources, based on (U.S. Energy Information Administration 2010)

This includes the direct use of electricity as well as the losses for the generation, transmission and distribution. The industrial primary energy demand is expected to increase by 38 % to 344 quadrillion Btu until 2030, compared to the year 2007. Electricity remains the essential energy form in 2030 with 43 %, an increase of 58 % relative to 2007 (U.S. Energy Information Administration 2010).

Due to the strong reliance on fossil resources, the conversion of energy in the economic system is inherently linked to carbon dioxide emissions. In order to describe the impact on the ecological system, the industrial primary energy demand and the associated carbon dioxide emissions of economies with different economic performance are compared. The economic performance is expressed through the Gross Domestic Product (GDP) per capita, a common measure for the

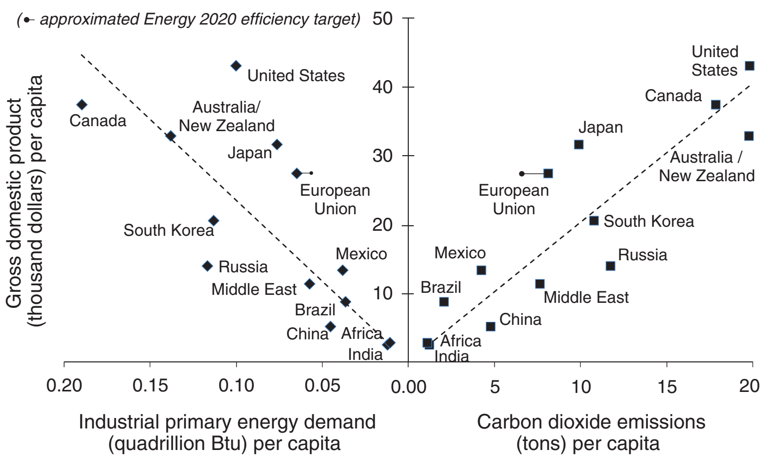


Fig. 2.2 Trends in industrial primary energy demand and energy-related carbon dioxide emissions, based on (U.S. Energy Information Administration 2010)

standard of living (Goossens et al. 2007). Figure 2.2 illustrates the GDP in relation to the primary energy demand and energy-related carbon dioxide emissions for 13 economies (referenced 2007) (U.S. Energy Information Administration 2010). The results of the analysis show that the industrial energy demand and emissions correlate in a linear fashion with the economic performance. Each 1 % increase in GDP is associated with an increase of primary energy by 0.05 % (the equivalent to 5 trillion Btu) and 0.54 % in carbon dioxide emissions.

With regard to the growth of (emerging) economies, the increase of the primary energy demand and the emissions of carbon dioxide as the most abundant greenhouse gas are expected to rise (International Energy Agency 2009). Studies of the *Club of Rome* revealed already in 1972 that the impact of economic growth goes beyond the capacity of the ecological system (Meadows et al. 2005). While the availability of fossil resources and the renewal rate of biogenic resources limit the use of primary energy in the economic system, the ecological system is bound by the ability to absorb waste and emissions without endangering the stability of the ecosystem (Meadows et al. 2005). The threat of climate change and the impending scarcity of energy sources led therefore to the elaboration of the Concept of Sustainable Development by the United Nations:

Sustainable development is development that meets the needs of the present without compromising the ability of future generations to meet their own needs. (World Commission on Environment and Development 1987).

The pursuit of a sustainable development has a broad scope taking into account economic, ecologic and social dimensions. The ecologic dimension is concerned with the interaction between the economic and ecologic system. It concentrates on the preservation of the ecosystem as well as the compliance of economic activities with the capacity of the ecologic system to provide resources and absorb emissions (Herrmann 2010; Dyckhoff and Souren 2008). Three strategies can generally be differentiated to enhance the ecological sustainability (Huber 2000; Dyckhoff and Souren 2008):

- *Sufficiency* refers to the self-determined limitation of all activities in the economic system in order to reduce the impact on the environment. It is implicitly noted in the definition of a sustainable development proposing the renunciation of consumption as part of an ecologically appropriate life style.
- *Efficiency* is inspired by the concept of technological progress and aims at the improvement of the input–output relations of existing transformation processes towards minimum input or maximized output levels. It is considered as the most cost-effective strategy providing immediate benefit.
- *Consistency* means the adaption of transformation processes ensuring coherence and compatibility of the renewable and non-renewable flows between the economic and ecologic system.

In order to envision thoroughly the ecologic dimension of a sustainable development, these strategies are specified through rules of conduct as well as legal directives (Dyckhoff and Souren 2008; International Energy Agency 2009). One of several examples is the regulatory framework *Europe 2020*, which specifies the three strategies of the ecologic dimension in terms of increasing energy efficiency, expanding the energy conversion from renewable sources and reducing greenhouse gas emissions by 20 % until 2020, relative to 1990 levels (European Commission 2010). To illustrate the implications of this framework on the European industrial sector, the mandatory reduction in the primary energy demand and carbon dioxide emissions are approximated for the increase in energy efficiency in Fig. 2.2 based on data from 2007 (U.S. Energy Information Administration 2010, 2007). Under the assumption of a steady GPD per capita until 2020, an increase in energy efficiency by 20 % demands a reduction of 13 % in the primary energy demand. Regarding the energy-related carbon dioxide emissions, this leads to a mandatory abatement of 19 % relative to 2007 in order to comply with the specified strategies.

To achieve the reduction in primary energy demand carbon dioxide emissions, a set of policies is extensively being developed and applied in order to amplify the adoption of energy-related instruments and the incorporation of energy efficient technology in the industrial sector. These include energy audits and energy management schemes as well as comparative assessments of the energy consumption for energy labelling (Verein Deutscher Ingenieure e.V. 1998; International Standard Organization 2011; European Parliament and Council 2009; European Commission 2010). The intention of these policies is to provide support for the implementation of (management) processes and systems in the industrial sector that help to improve the usage of energy (International Standard Organization 2011). An initial prerequisite for energy-related improvement described in all policies is to gain awareness about existing energy flows in order to identify improvement potentials (Herrmann 2010; Müller et al. 2009).

2.2 Energy Flows in Transformation Systems

Energy is a scalar quantity that exists in different forms as chemical, electrical, magnetic, mechanical or thermal energy. It is indirectly determined through measuring energy changes (Dincer and Rosen 2007). The different forms of energy can be converted via work and heat into one another at the expense of degradation in quality due to the thermodynamic irreversibility (Atkins and de Paula 2010). With respect to the conversion, energy can generally be distinguished into primary energy (e.g. as embodied energy in coal) and secondary energy (e.g. transformed into electrical energy) (Harvey 2010).

Energy is a mandatory input for industrial production. It can only partially be replaced by other resources (factor of peripheral substitution) (Rager 2008). Industrial production encompasses all activities that create value through the transformation of resources, components or parts to desired goods (Bellgran and Säfsten 2010; Dyckhoff and Spengler 2010). The terms *production* and *manufacturing* are often used interchangeably (Kalpakjian and Schmid 2001). To differentiate both terms, a systems-based distinction is chosen in accordance to the

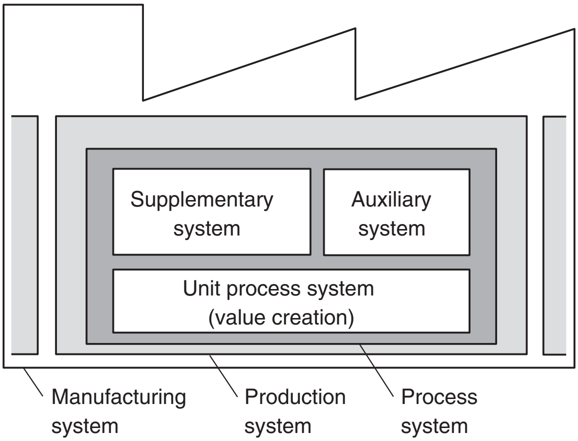


Fig. 2.3 Perspectives for energy analysis in manufacturing systems, adapted from (Bellgran and Säfsten 2010; Schieferdecker 2006)

definition provided by the International Academy for Production Engineering (CIRP).

Manufacturing is defined as … a series of interrelated activities and operations involving the design, materials selection, planning, production, quality assurance, management and marketing of the product of the manufacturing industry (CIRP 1990).

Production is … the act or process (or the connected series of acts or processes) of actually physically making a product from its material constituents, as distinct from designing the product, planning and controlling its production, assuring its quality (CIRP 1990).

Based on these definitions, a manufacturing system entails the activities within a plant or factory. It embraces the production system, which consists of the elements process, operand and operator. The operand is transformed in the process element, which is guided by the operator. The interrelation between these three elements determines the structure of the production system and affects the transformation process (Bellgran and Säfsten 2010). The process element can be further diversified into supplementary, unit process and auxiliary subsystems (see Fig. 2.3) (Schieferdecker 2006). Unit processes are decentralized operating entities, which directly use energy to perform the designated value creation. An indispensable precondition for the unit processes is the operation of supplementary systems. These are centrally operating entities that convert supplied energy in other forms meeting the requirements and demands of the unit processes. This includes systems that provide compressed air, filtering devices for cutting fluids or voltage transformers. The function of the auxiliary system is to maintain the operability of the entire system (e.g. ensure thermal and visual comfort) (Rager 2008). The supplementary systems, which are not directly associated to the unit processes, and the auxiliary systems are jointly considered as technical building services (Herrmann 2010).

From an energy-oriented perspective, these three entities of the process system represent the origins of energy demand in manufacturing systems, which accumulate on higher system levels to the absolute demand. To analyse the energy demand in production, two methodological approaches can be distinguished. While the energy-related assessment on production or manufacturing system level is referred to as macro-analysis operating with aggregated data, the objective of a micro-analysis is the detailed specification of the energy demands in unit process systems (Binding 1988).

On average, manufacturing systems demand chemical and electrical energy, which is transformed within the supplementary and auxiliary systems into thermal and mechanical energy (Müller et al. 2009). A review of the environmental statements of three Volkswagen automotive manufacturing systems exemplifies that electrical energy is the dominating form of energy with 48–65 % of the total demand (Volkswagen 2011a). While this aggregated data is commonly available, an assignment to the entities on the process system is absent. Therefore, a case study was performed for a metalworking production system in the automotive industry intending to disaggregate empirically the energy demand. The study included the unit process and supplementary systems with more than 15 machine tools as well as three centralized filtering devices and three mist collectors for cutting fluids (excluding the compressed air systems). The results point out that 56 % of the total electrical energy is used in unit processes and 44 % in supplementary entities. An alternative case study for a different metalworking production system in the automotive industry confirms the distribution of the energy shares (Bode 2007). Since a substantial share of electrical energy consumption originates in unit process systems, the electrical energy demand of these systems is subsequently analysed as a basis to deduce energy-related measures for improvement.

2.2.1 Electrical Energy Demand of Machine Tools

In production systems, inputs are transformed into tangible outputs through a sequence of technological processes. These processes are carried out by machinery. Machine tools represent a distinct class of metalworking machinery, which are defined as stationary operating, assembled systems fitted with a drive system other than directly applied human effort (Schischke et al. 2011a). They consist of joined parts and moving components enabling the entire system to perform a complex, useful function, which is the geometric forming, shaping or joining of workpieces in a defined quality using appropriate tools and technologies (European Parliament and Council 2006; Tönshoff 1995; Deutsches Institut für Normung e.V. 1985). The classification of machine tools relates to the structure and taxonomy for manufacturing processes according to the DIN standard 8580 (Deutsches Institut für Normung e.V. 2003; Brecher and Weck 2005).

A machine tool consists generally of a machine frame, guides, drives and control units (Tönshoff 1995). The integrated electrical components are signal elements, drives and actuators as well as wiring and measuring systems (Weck and Brecher 2006b). The electrical energy demand results from the temporal

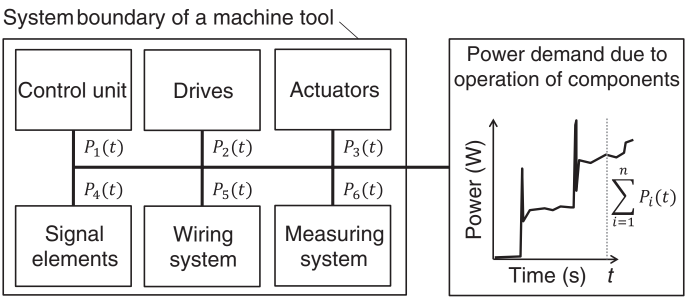


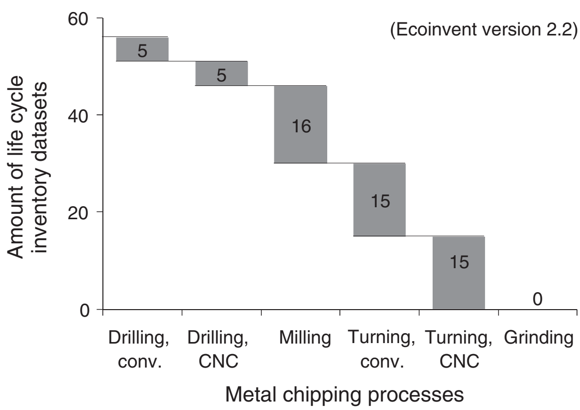
Fig. 2.4 Accumulation of power demands in a machine tool system (Zein et al. 2011)

accumulation of the individual power consumption for each component (see Fig. 2.4). Throughout the operation of the machine tool, process-induced performance requirements affect the power demand of the components. Depending on the structure of the machine elements and their operation, the power consumption is therefore not static but rather dynamic (Wolfram 1986; Bartz 1988).

The electrical energy demand of machine tools is rarely specified and known. Fractional information on energy requirements is provided for instance in life cycle inventory databases (e.g. Ecoinvent) for machining unit processes (Steiner and Frischknecht 2007). Yet, this information is restricted to a selection of machining processes and based on estimations providing aggregated and averaged data about the energy demand (Steiner and Frischknecht 2007). Figure 2.5 depicts the available inventory unit processes provided in the latest version of Ecoinvent supplied by the Ecoinvent Centre. With regard to the averaged values and underlying estimations in the existing inventory datasets, an in depth specification is generally recommended in case the scope centres the machining operation (Steiner and Frischknecht 2007).

In order to gain insight on the specific energy requirements of a machine tool, the energy demand is predominantly determined through power measurements. Power meters enable to capture the power demand by recording the current,

Fig. 2.5 Availability of life cycle inventory data, derived from (Steiner and Frischknecht 2007)



voltage and phase angle between voltage and current (in a three-phase system). By including the distortion in phase, the effective power is distinguished from the apparent power as the actual power delivered (Parthier 2010). The resulting power profile provides a basis to revise the operational modes and related power characteristics (Eckebrecht 2000). It is moreover an important instrument for time studies, which enable to distinguish productive and non-productive time shares of machine tool operation (Brecher et al. 2010; Kellens et al. 2011a).

Reviewing the power profile of an exemplary grinding process in Fig. 2.6, the activation of the machine tool and spindle as well as the material removal can be identified as operational modes. With regard to the power demand, a variable and fixed portion can generally be differentiated (Wolfram 1986; Dahmus and Gutowski 2004). The fixed power P_{fixed} covers the constant demand, which is necessary to ensure a functional mode of operation (e.g. waiting for operation). The process-induced portion relates to the power consumption for proceeding the machining process without touching the workpiece (so called air-cut) and the material removal capacity (Eckebrecht 2000; Wolfram 1986).

Power measurements represent the initial step to quantify the individual process energy W_{p} and fixed energy W_{f}, which are derived by integrating the power demands of machine tools over the processing period (1) and (2) (Binding 1988).

$$W_p = \int_{t_0}^{t_1} P(t) - P_{fixed} \; dt \tag{1}$$

$$W_f = \int_{t_0}^{t_1} P_{fixed} \, dt \tag{2}$$

A diversification of the fixed energy demand can be obtained from the power profiles by allocating power levels to the activation or operational modes of

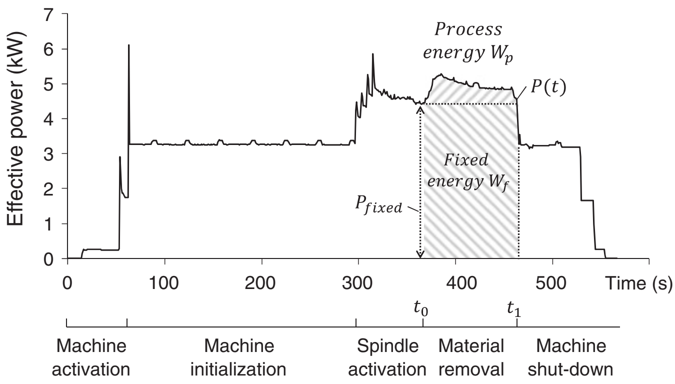


Fig. 2.6 Measured power profile for a grinding machine

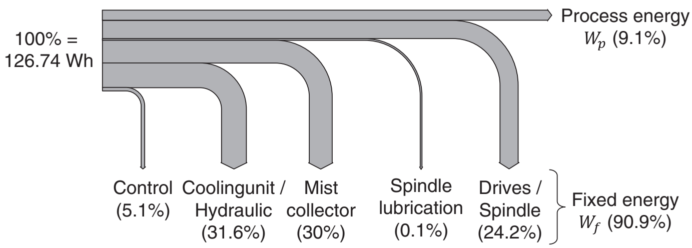


Fig. 2.7 Sankey diagram of energy flows for a material removal process

machine components (Eckebrecht 2000; Dietmair and Verl 2009a). In Fig. 2.7, the energy demands of components are visualized in a flowchart for the given grinding process based on the corresponding power characteristic during the machine activation, initialization and spindle activation. The allocation of energy demands to the components is exemplified in Appendix A.

As indicated in Fig. 2.7, the energy demand is determined by the process and individual machine characteristics. While the process energy depends on the material properties, selection of tools and process parameters ensuring an effective material removal, the machine characteristic is bound to the type of machine tool and the power demand of the integrated electrical components (Wolfram 1986; Binding 1988). In order to ease the effort to carry out power measurements, descriptive models have been developed that quantify energy demands based on material properties and technological parameters (e.g. chip thickness). These models rely on force prediction and enable to specify the tool tip energy for cutting the material (Rowe 2009; Kienzle 1952; Astakhow and Outeiro 2008; Wolfram 1986). This energy demand, however, takes up just a small share of the absolute energy. It is primarily used to analyse process restrictions and define technical requirements for the selection of spindles and machine tools (Kalpakjian and Schmid 2001). The extension of these cutting energy models towards predicting the process or total energy demand has been deficient in accuracy and applicability due to the machine-related variability in composition and specification (Wolfram 1986; Binding 1988; Dahmus and Gutowski 2004).

2.2.2 Trends Affecting the Power Demand of Machine Tools

Advances in manufacturing accuracy and processing performance have intensified the application of automation technology in machine tools. In addition to the automation of operational functions as handling or processing, modern machine tools have evolved to highly automated complex systems equipped with a variety of electrical means to monitor and maintain the operability and process quality (Weck and Brecher 2006a; Kalpakjian and Schmid 2001).

Power ratings represent as an attribute of machine tools a measure of the potential power use under individually assumed operating conditions. It is assigned by the machine tool manufacturer for an observed system designating for instance

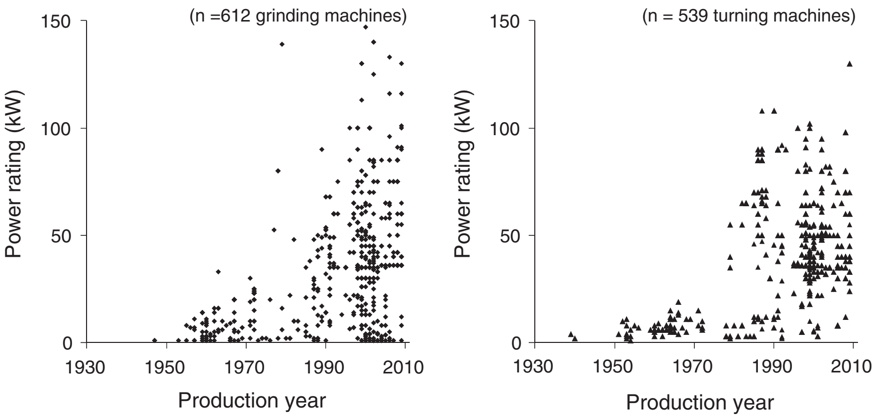


Fig. 2.8 Empirical long-term trends in power rating for machine tools

the minimum requirements for the power supply (Müller 2001). The power rating does not necessarily comply with the actual power demand providing nevertheless an indication about the power capacity (Li et al. 2011). Using the power rating as evaluative parameter, the effect of the increasing machine complexity and automation on the power consumption has been analysed for a total of 1,100 grinding and turning machines. The data is derived from three automotive metalworking manufacturing systems in Germany providing machine tool datasets for a time period of more than 70 years. Reviewing the long-term trend in Fig. 2.8, a substantial amplification in power ratings can for instance be determined for grinding and turning machines over the last three decades. The enveloping threshold in power rating increased from 24 kW around 1980 up to 100 kW with outliers even exceeding 147 kW. This trend appears to be interrelated to the introduction of computerized numerical controls in machine tools at the end of the 1970s (Degner 1986). It increased with the accelerated integration of electrical equipment (e.g. controls, sensors and actuators) improving the machining performance (Kalpakjian and Schmid 2001).

Besides the enhanced usage of automation technology, the origins of a higher power consumption of machine tools can be attributed to an increased power consumption of its integrated components. The demand for a higher processing performance has for instance been satisfied by increasing the torque of the main spindle resulting in higher power demands (Bode et al. 2008). As an example, the growth in output power of main spindles is illustrated in Fig. 2.9 indicating the trend for the last 25 years.

The results of these two empirical datasets specify a general upward trend in power consumption of machine tools induced by automation and component performance. Complementing the review of energy-related trends, an analysis of 30 machine tools performed by Degner provides an insight into the effective energy requirements to conduct the material removal (Degner 1986). The observations

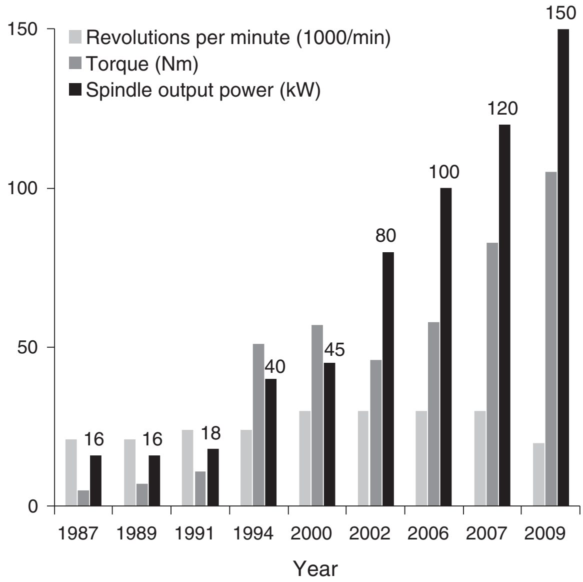


Fig. 2.9 Growth of main spindle performance (Reference Type HSK63) (Bode et al. 2008); updated in (Brecher and Bäumler 2011)

conclude for instance that the energy ratio of material removal to the absolute demand varies between 0.8–54 % with an average of 19 % among the observed machine tools. Degner deduces that the remaining share can accordingly be allocated to conversion losses within the components of the machine tool. In addition, the analysis points out the relevance of the fixed power exceeding the demand to conduct the material removal by a factor of up to 40 (Degner 1986). A comparison of two milling machines underlines this perception substantiating the increase in the fixed demand from a manual to an automated system (see Fig. 2.10) (Dahmus and Gutowski 2004). While the data provided by Dahmus and Gutowski and Degner reflects the power requirements of machine tools older than 20 years, it can be assumed that the correlations remain valid until today. This amplifies the relevance of the fixed power with respect to the described increase in power rating.

2.2.3 Improvement Measures for Electrical Energy Demand

With regard to the diversity of factors influencing the energy demand of a machine tool, a structured overview about available measures to improve the energy demand is obtained in this section. It is performed in order to provide insight about the obtainable potentials and focus point of measures. More than 100 energy-related measures have therefore been depicted from the Best Environmental Practice Manual as well as reports of the industry initiative Blue Competence and European Commission Product Group Study on Machine Tools (Schischke et al. 2012b; Prolima 2008).

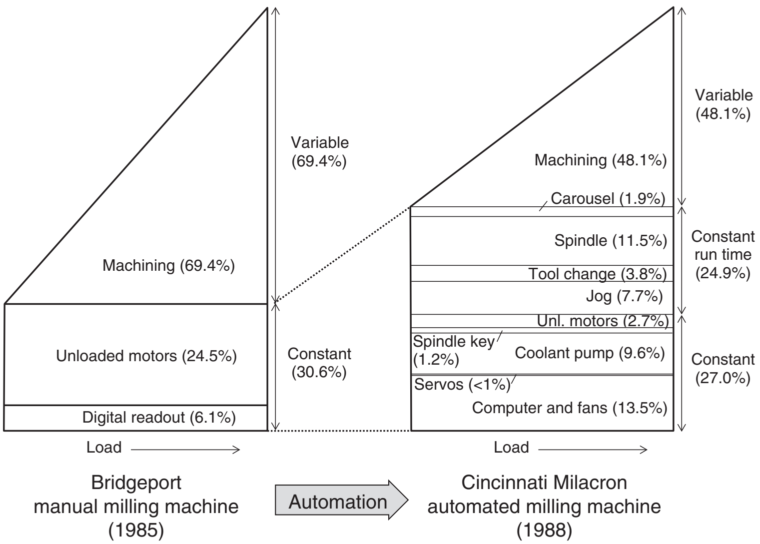


Fig. 2.10 Effect of automation on the fixed power demand (Dahmus and Gutowski 2004)

Improvement measures are fundamentally pursuing the objectives to minimize the energy losses in the provision, reduce the demand of the transformation and minimize the losses of the transformation (see Fig. 2.11). As power and time are the two factors directly relating to the electrical energy demand, improvements have either a temporal or a power-related characteristic. Measures to reduce the power consumption include for instance the replacement of machine components as hydraulics, drives or spindles with less power consuming alternatives (Neugebauer et al. 2008; Abele et al. 2011). Alternatively, the reduction of moving masses in machine tools using aluminium as lightweight material instead of steel has shown additional saving potential reducing the power demand in operation (Dietmair et al. 2010). In contrast, temporal advances aim at improving the

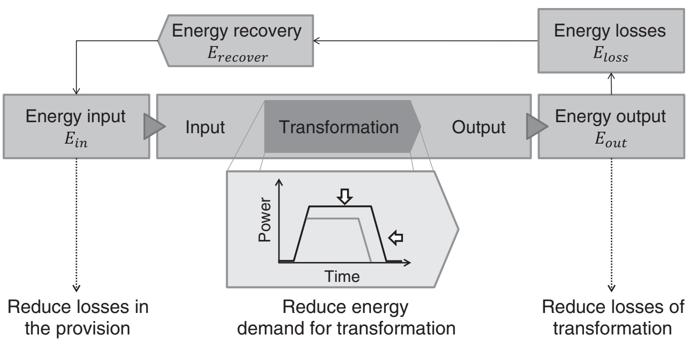


Fig. 2.11 Objectives of energy-related improvement measures, adapted from (Fanuc 2008; Müller et al. 2009)

machining task (e.g. near-net-shape machining) and the process design by increasing material removal rate or avoiding non-operational times in fixed power mode (Fanuc 2008; Heidenhain 2010; Müller et al. 2009). Synchronizing the acceleration and deceleration of a machining spindle and tool feed system to avoid idle times led for instance to an energy reduction of 10 % compared to the former operating conditions (Mori et al. 2011).

Energy losses E_{loss} represent the share of input energy E_{in} that is not contributing to the transformation and liberated as heat (Verein Deutscher Ingenieure e.V. 2003). Apart from the usage of heat emissions as a source for facility heating purposes, improvement measures predominantly intend to minimize the intensity of energy losses by reducing friction, leakages or process temperatures (Bartz 1988; Neugebauer et al. 2011). Additionally, measures can be implemented to recover energy $E_{recover}$ through kinetic buffering or heat recuperation (Müller et al. 2009; Diaz et al. 2010a).

Complementary to the consideration of objectives, measures can be allocated to the point of action comprising the process, component or entire machine tool. This structural assignment of measures enables to consider the effort and complexity to adopt an improvement (Binding 1988). While a process improvement can instantly be applied (e.g. variation of material removal rate), changes in the design of the machine tool or components are constrained and may therefore be contemplated in subsequent machine tool generations (Zein et al. 2011). Based on the energy-oriented classification of measures according to the objective and point of action, the identified improvement measures have been clustered. Figure 2.12 illustrates the selection of measures, which could clearly be assigned to the given set of categories. The results indicate a high availability of energy-reduction measures with a strong design emphasis of 40 % on the process, 35 % on the component and 25 % on the machine tool. Considering the reduction of energy losses due to

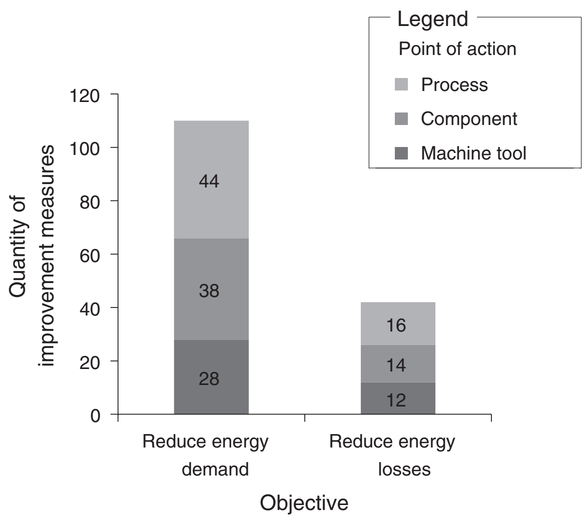


Fig. 2.12 Availability of improvement measures for machine tools, updated from (Zein et al. 2011)

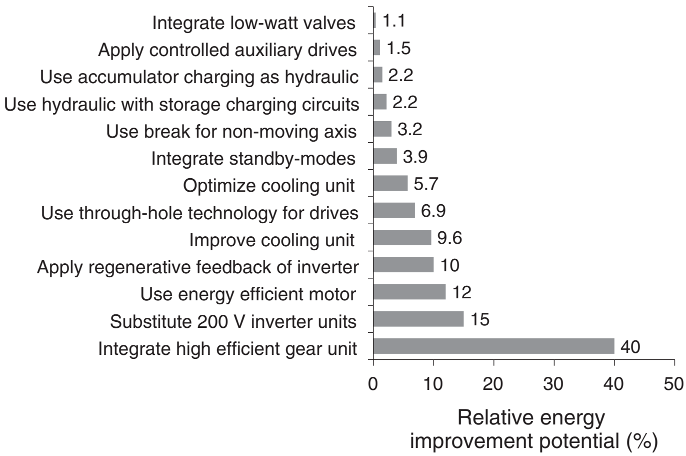


Fig. 2.13 Potentials of energy-related improvement measures, data derived from (Schischke et al. 2012b; Hegener 2010)

energy conversion, a minor share of measures was identified which can be attributed equally on all three points of action with limited variations.

Although more than 100 measures have been derived, information about the diffusion rate of measures in industry is restricted in availability. The same applies to information about the attainable energy savings, which is an essential prerequisite for the valuation of the profitability of improvement measures. An indicative ranking of measures has therefore been established providing an insight about the estimated relative improvement potential, which include savings of up to 40 % (see Fig. 2.13) (Schischke et al. 2012b; Hegener 2010). The absolute obtainable potential by aggregating a set of measures is sparsely exemplified for specific machine types. The results of prototypical implementations indicate an energy reduction of 30 % compared to the original machine system (Hegener 2010).

2.2.4 Energy Efficiency Gap

The motivation to enhance the energy demand is confronted with diverse barriers sustaining an "energy efficiency gap" (Jaffe 1994; Bunse et al. 2011). This phenomenon is defined as the deviation between the actual and ideal energy requirement of energy-using systems. It represents an unexploited improvement potential, which remains concealed due to failure and inertia to implement cost-effective measures (Baumgartner et al. 2006; Jaffe 1994).

Reviewing the literature on the origins of energy-related barriers inhibiting improvement, four aspects can generally be attributed regarding machine tools. These are specified as imperfect information, legal restrictions, profitability risks

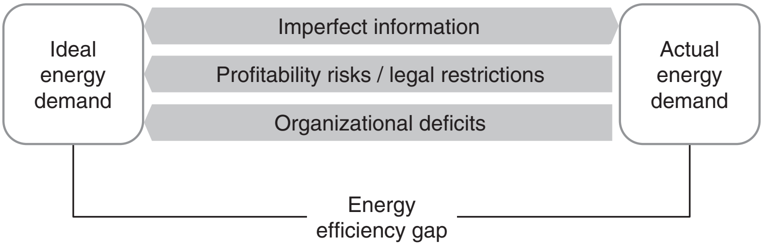


Fig. 2.14 Obstacles inducing the energy efficiency gap

and organizational deficits (see Fig. 2.14) (Nolte and Oppel 2008; Wanke and Trenz 2001; Baumgartner et al. 2006; International Energy Agency 2007; Seefeldt et al. 2006; Schleich 2009). The list is not exhaustive, but intends to provide an insight on the major causes contributing to the energy efficiency gap.

2.2.4.1 Imperfect Information

The attainment of energy-optimal operating conditions necessitates comprehensive information about the actual energy demand of machine tools and the benefits gained by associating adequate measures (Jaffe 1994).

Reasons for the lack of information about saving potentials originate in imperfect information about the current energy requirements and consumption patterns (Koopmans and te Velde 2001; Schleich 2009). This applies to information about the power demands as well as operating performance indicating the share of energy spend in productive and non-productive modes. The availability of energy-related information is commonly restricted due to the fragmentation and heterogeneity of machine tools and an unwillingness to perform time-consuming metering procedures (Wanke and Trenz 2001; Stasinopoulos et al. 2009).

The investment in energy improvements can furthermore fail due to imperfect information about suitable measures as well as limitations to evaluate the obtainable potential, reliability and applicability. The evaluation is usually aggravated by the prototypical implementation of measures in isolated case studies, which impedes the transfer and assessment of potentials in prevalent applications (Wanke and Trenz 2001). From this follows that as long as the performance of an activity and benefit of improvement measures remain unknown to the manufacturer or user, an implementation is unlikely to take place (Schleich 2009).

2.2.4.2 Legal Restrictions

The origins of legal restrictions are related to in the formalisms of business activities with third parties and legislative provisions. Restrictions can impede the implementation of energy improvement measures if warranty requirements and contract specifications are violated or additional testing and inspection regulations are implied (e.g. machine capability examinations) (Seefeldt et al. 2006).

2.2.4.3 Profitability Risks

From an economic perspective, failure to invest in cost-effective improvement measures can be substantiated by the inability to predict and quantify additional costs, which are associated with the implementation (Schleich 2009). These costs arise from all activities to obtain detailed energy-related information (e.g. metering power demands), to prepare and execute the measure as well as to revise the effect of the improvement. In total, these unpredictable costs can extensively exceed the envisaged energy savings (International Energy Agency 2007; Schleich 2009).

While up to 17 % of the life cycle costs can be associated for instance to the energy demand of a machine tool (see Fig. 2.15), the overall industrial energy costs take up however on average 2.2 % of the gross production value throughout the German metal processing sector (referenced to 2009) (Abele et al. 2009; Federal Statistical Office 2011).

This corresponds to 7.3 % of the labour costs and strengthens the perceived minor relevance of energy improvements obstructing investments (Wanke and Trenz 2001; Galitsky and Worrell 2008). Besides, alternative investments in quality or process technology are expected to provide higher benefits in compliance with restrictive payback periods than energy-related measures (International Energy Agency 2007; Seefeldt et al. 2006).

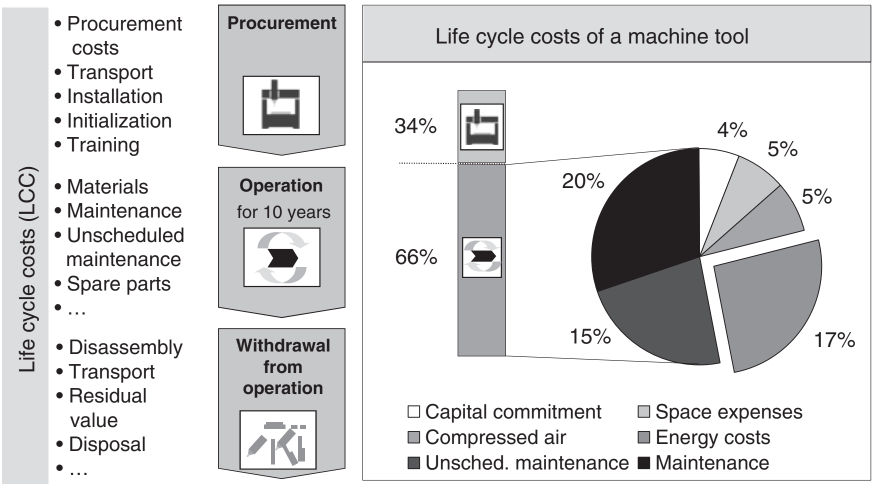


Fig. 2.15 Life cycle costs of machine tools, adapted from (Abele et al. 2009; Dervisopoulus et al. 2006)

2.2.4.4 Organizational Deficits

In addition to the given barriers, there are also organizational limitations relating to management constraints and split incentives. Lack of time, motivation and competence have been identified as the major management factors impeding the implementation of energy-related improvement measures (Nolte and Oppel 2008). Energy is therefore not among the strategic priorities of the top management indicating energy savings as rather incidental (Seefeldt et al. 2006; Schleich 2009).

Another organizational restraint which should not be underestimated relates to shared responsibilities impeding the overall incentive to invest in energy improvement measures (Wanke and Trenz 2001; International Energy Agency 2007). These limits arise from split incentives, when energy savings are not directly accountable to the originator and accrue elsewhere (Nolte and Oppel 2008; Schleich 2009). Split incentives prevail for instance between a machine tool builder and user about the integration of energy saving measures. It is only beneficial for the machine tool builder if additional profits can be gained. From a user perspective, investments may fail if information about the potential to recover the additional costs through energy savings is neither existent nor verified. Thus, imperfect information and the associated transaction costs impede to go beyond the organizational barrier (Schleich 2009; International Energy Agency 2007).

Despite the characterization of potential barriers obstructing the improvement of machine tools, the energy efficiency gap for machine tools has neither been evidenced nor quantified. This is mainly attributable to a lack of evaluative information about the ideal energy demand of machine tools as well as the actual energy demand of prevalent machine tools in operation. However, the variety of energy saving measures and associated potentials provide an indication that a considerable improvement potential remains unused, so far enabling only estimations about the magnitude of the energy efficiency gap.

2.2.5 Findings

Synthesizing the aspects that obstruct the energy-related improvement of machine tools, the importance to gain evaluative information about the energy efficiency gap is emphasized. The quantification of the energy efficiency gap is however bound to the ability of measuring the divergence of the actual energy usage in relation to the ideal energy reference providing insight on the associated magnitude of improvement potential.

Nevertheless, information constitutes solely a necessary but not sufficient condition for the realization of improvement. The sufficient condition comprises the operationalization of this information in management control mechanisms (DeCanio 1993). As a consequence, information and control represent the means to mind the barriers and guide the development of cost-effective improvement policies (Schleich 2009; Jaffe 1994).

2.3 Performance Management

Performance management strives to improve the performance of activities ensuring that actions are initiated to bridge a gap between the actual and designated ideal performance (Ferreira and Otley 2009). The evaluation of a performance gap through measurement constitutes the main objective of performance measurement as an integral element in the performance management process (Neely et al. 2005; Folan and Browne 2005).

Revising the fundamentals of the term performance, the process and the implementation of performance measurement as a means to gain evaluative information about performance is subsequently introduced in this section. Extending the scope towards the initiation of improvement actions, the integration of performance measurement into the process of performance management is described taking a cybernetics perspective on management control. By specifying performance management in an energy-oriented context, the capacity to determine ideal energy demands is reviewed as a basis to quantify and bridge the energy efficiency gap for machine tools.

2.3.1 Performance Measurement

Performance is an ambiguous term with diverse definitions adapting the specific context of applications and stakeholder perspectives (Hilgers 2008; Krause and Mertins 2006). Reviewing the commonalities among existing definitions, performance can be specified as the capacity of an activity to meet expectations. These are expressed by achieving a quantified target, which is evaluated in the dimensions effectiveness and efficiency (Erdmann 2002).

Effectiveness reflects the results of an activity as a qualitative measure. It obtains a strategic perspective ensuring that activities are initiated, which provide a contribution towards defined objectives (Hilgers 2008). In contrast, efficiency obtains an operational, transition-oriented perspective and valuates the degree of resource usage to meet an aspired result using quantitative metrics (Braz et al. 2011). Both measures combined form the evaluative dimensions of performance verifying the success of an activity (Lichiello and Turnock 1999).

In order to facilitate a better understanding of performance, the main characteristics have been deduced by (Krause and Mertins 2006). Accordingly, performance

- relates to relevant financial and non-financial characteristics and the gained benefit of a system,
- enables a multidimensional perspective,
- is influenced by the selected focus and thematic background,
- obtains a future- and action-oriented perspective on processes,
- originates in activities,
- and can be assessed using absolute or quantitative indicators (Krause and Mertins 2006).

The process of generating information about the effectiveness and efficiency of an activity is defined as performance measurement (Sturm 2000; Braz et al. 2011). According to Waggoner et al., it encompasses the

monitoring of performance, identification of areas that are in need of attention, enhancing motivation, improving communications, and strengthening accountability (Waggoner et al. 1999).

In addition to the evaluation of performance, performance measurement comprises also the establishment and implementation of processes to observe the performance and direct attention by providing information on a persistent basis (DeGroff et al. 2010; Stoop 1996). The process of performance measurement is described in the next section revising the elements and actions to formulate a target and to derive evaluative information about the performance of an activity.

2.3.2 Process of Performance Measurement

Reviewing the literature on the performance measurement process, an extensive variety of approaches can be identified. The elaboration of models for performance measurement ranges from brief descriptions on performed tasks, specifications of tools up to complete process guidelines (Bourne et al. 2003; Nudurupati et al. 2007).

A commonly proposed model to conduct performance measurement consists of four steps (Krause and Mertins 2006; Stoop 1996):

- *Diagnosis* encompasses all activities that relate to the review of objectives and requirements to implement the performance measurement. This includes also the definition of indicators, which are used to provide information about the performance in the subsequent steps.
- In the *projection* phase, the performance target is set as a quantitative indicator level expressing the commitment to achieve a defined performance.
- Within the *valuation* phase, the achieved performance is determined and compared with the performance target enabling to assess the effectiveness and efficiency of the observed activity.
- The final phase considers the *application* of the obtained performance information to pursue improvement.

In addition to this four step model, which is affiliated from the Deming-cycle, a three step procedure is anticipated by Stivers et al. and applied by Grüning. It sets a stronger emphasis on the measurement aspect within the performance measurement process (Stoop 1996). It stresses the *identification of performance factors, the measurement* and the *application* to pursue the defined target (Grüning 2002). Figure 2.16 depicts the commonalities between a comprehensive implementation approach in relation to the four and three step model. Having identified the three basic elements to conduct a performance measurement, the associated methods and tools performed in each step are subsequently described in detail.

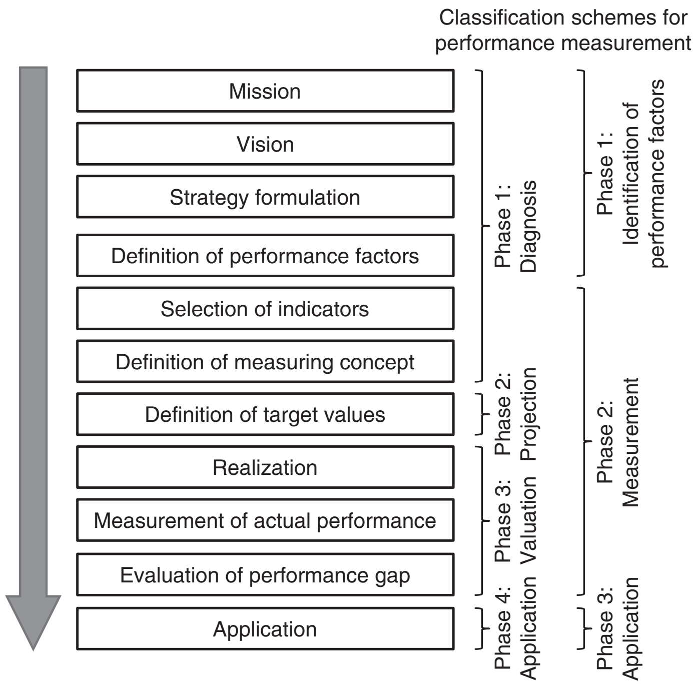


Fig. 2.16 Representation and classification of the performance measurement process (Grüning 2002)

2.3.2.1 Identification of Performance Factors

Measuring the performance of an activity demands initially to identify all aspects that affect the realization of an objective. These performance factors can for instance be extracted from strategies, which arise from the elaboration of visions and missions (Grüning 2002). From an economic perspective, five different types of performance factors are generally distinguished and categorized into traditional and modern factors. Physical and financial resources are jointly considered as traditional, well-established performance factors. In contrast, modern factors are addressing immaterial resources, processes and systems (Grüning 2002).

The selection of performance factors encompasses an evaluation of the relevance, importance and quality of the factor to represent the objective (Grüning 2002). In case multiple performance factors are identified, the interrelations between the factors have to be analysed in order to avoid ambiguous results from the performance measurement. By finally consolidating a structured set of performance factors, the objectives are operationalized into a performance measurement system, which builds the foundation for the subsequent measuring process (Hilgers 2008; Stoop 1996).

2.3.2.2 Measurement of Performance

The process of measuring performance starts with the conversion of identified performance factors into performance measures (Grüning 2002). Measures are metric indicators, which provide information about the characteristics of the performance factors in quantitative standards of measure (Blackburn 2008). Indicators can generally be expressed in form of relative numerical ratios and absolute terms (Jasch and Tukker 2009). An overview about possible indicators to measure the performance of processes is illustrated in Fig. 2.17. Accentuating a specific monitoring scope, it differentiates the indicators productivity, efficiency and profitability. The productivity metric obtains from a production theoretical perspective a purely physical input/output-perspective. The indicator on efficiency valuates the process by relating the expected resource usage to the actually used resources (Bellgran and Säfsten 2010). The profitability incorporates preferences regarding the economic implications (revenues and costs) of the transformation (Dyckhoff 2006). A thorough review on the interrelations between productivity and efficiency is provided in Sect. 4.3.2.

The selection of indicators has to ensure that the informational value about the performance factor is reliable and valid. The term reliability relates to the accuracy and reproducibility of the indicator to provide distinct information about the performance factor. The reliability of the indicator is a prerequisite for the assessment of validity. The validity of an indicator valuates the responsiveness and precision to react effectively to changes (Grüning 2002).

In addition to the informational value, the costs to determine and quantify the indicators are exerting a strong influence on the selection process. The measurement costs comprise all activities, which are necessary to collect the relevant data in order to appraise the indicator. Generally, the quantification of indicators for traditional performance factors is less expensive than for modern factors, as

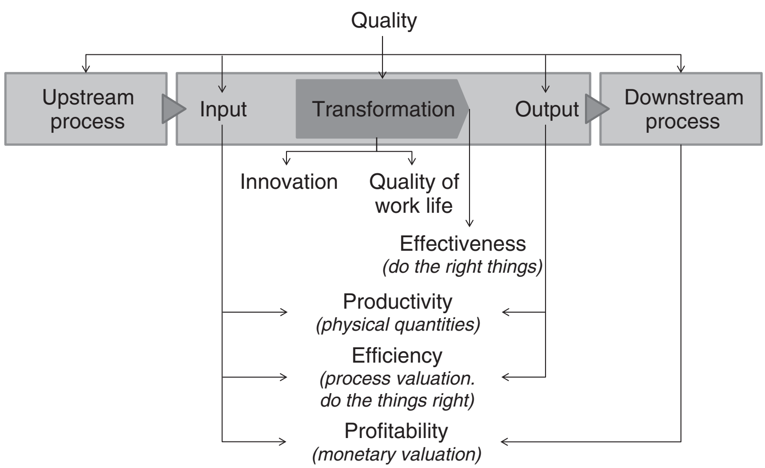


Fig. 2.17 Common indicators to measure the performance of processes, adapted from (Sink and Tuttle 1995; Bellgran and Säfsten 2010)

most indicators depend on existing data. Considering the selection of indicators, the reliability, validity and measurement costs have to be in alignment with the requirements to perform the measurement (Grüning 2002).

Following the determination of indicators, the process of defining target values and assessing the performance is conducted. By specifying a threshold value for each indicator, the performance targets are quantified representing a commitment of the anticipated level of performance (Stoop 1996). In order to ensure a successful operation of the performance measurement, it is essential to place an objective, realistic and challenging target value (Stoop 1996). Particular approaches to define and identify target values are subsequently introduced:

- Deriving performance targets from *intuition* is a simple method demanding little effort and costs. In situations in which no information about the performance is available, intuition enables to anticipate subjectively a threshold for the performance. However, this approach does not meet any of the given evaluative performance criteria. It should therefore only be applied once no other way of determining a threshold can be obtained (Stoop 1996).
- The introduction of a *monitoring* system supports the quantification of target values by reflecting former performance tendencies. This enables to determine an ideal target value based on observed performance levels. Implementing a monitoring system demands to consider that the performance threshold is concerned with the evaluation of the past. It does not enable to presume advances in performance due to improvement (Grüning 2002).
- *Quantitative models* inherit the characteristics of the evaluated system enabling to predict the performance. This allows an assessment of the actual performance under varying conditions and is the basis to derive the maximum attainable performance level. The usefulness of quantitative models depends however on the quality and the applicability of the model to perform accurate predictions (Nudurupati et al. 2007; Armstrong and Shapiro 1974). The evaluation of quality relates to the comprehensiveness of the underlying assumptions linking the real world and model. This also includes verifying the reliability of the predictions. Additionally, the applicability relates to the perceived quality of the model application indicated by the ability to resolve unknown information and the obtained benefit (Armstrong and Shapiro 1974; Stoop 1996).
- In addition to the quantitative models, target values can furthermore be obtained in form of *cooperative agreements* between all stakeholders, which exert influence on the performance (Grüning 2002). In this case, target values constitute essentially the willingness of stakeholders to contribute towards the improvement of performance (Bourne et al. 2003).
- *Strategic targets* represent another valuable source of information, which can be used to adopt performance thresholds. Nevertheless, it has to be noted that the conversion of strategic targets into performance targets contemplates a long-term perspective, which may require converting the targets for short-term periods (Grüning 2002).
- A final option to determine targets is the *comparative assessment*. It provides insight about obtainable levels of performance based on the comparison of

alternative solutions (Binding 1988). This enables on the one side to determine a common, averaged performance level, which sets the basis to define target values incrementally exceeding the quantified performance. On the other side, the comparative assessment strives to identify outstanding solutions among the revised alternatives, which represent best available solutions. The process to identify a reference with outstanding properties for comparative assessments is considered as benchmarking (Zhu 2009). The identified benchmark sets the target value that has to be obtained through performance improvements. An essential prerequisite to conduct a comparative assessment is in both cases the availability of alternative solutions, which are adequate for comparison (Stoop 1996).

Revising the capacity to determine objective, realistic and challenging target values, substantial differences and inabilities among all approaches become apparent. The capability of the methods to meet the selection criteria is approximated in Table 2.1 concluding the critical examination in literature. The definition of a target value is consequently considered as the most critical and challenging element in performance measurement (Centre for Business Performance 2004; Boyd et al. 2008). For that reason, the target value originates predominantly from empirical evidence in order to ensure the achievability in practical applications (Johnston et al. 2001).

Based on the specification of a target value, the actual performance is obtained through measurement. This demands the development of a measurement concept, which defines the procedures and tools to track the parameter value consistently. The actual performance is indicated by the obtained level of the parameter value on the indicator scaling (Grüning 2002). When considered individually, the actual performance level does not provide any use as a single indicator. Only through comparison with the corresponding target value, qualitative information on the performance is obtained (Cantner et al. 2007).

The evaluation based on the measured performance and defined target value is the starting point for the improvement process in the final step. It contemplates the

Table 2.1 Review of approaches to derive target values

		Approaches to define target values						
		Intuition	Monitoring	Quantitative models	Cooperative agreements	Strategic targets	Comparative assessment (average value)	Comparative assessment (benchmarking)
Properties	Objective	○	●	●	○	○	●	●
	Realistic	○	●	●	◐	◐	●	●
	Challenging	○	◐	●	◐	◐	◐	●

Characteristic value:

○ low	◐ average	● high

identification and implementation of activities to improve the performance striving to meet the target value.

2.3.2.3 Application of Performance Measurement

The consideration of performance measurement information in the context of decision-making is the last element in the performance measurement process. The results of the performance measurement provide evaluative information about prevalent gaps between the ideal and actual performance, which is used to derive and implement actions for improvement.

The use of information facilitates the valuation and communication of preceding performance trends serving the function to reward and motivate an impending, purposive behaviour (Krause and Mertins 2006). In addition, the results of the performance measurement enable a reconsideration of the feasibility to achieve the defined targets under the prevailing conditions. This can consequently lead to an adaption of target values (Hon 2005). The functional use of performance measurement is outlined in Fig. 2.18.

Providing information about the current performance and the obtainable improvement potential, performance measurement shares the characteristics of management control as element of the management process (Grüning 2002; Stoop 1996). The interrelation between the measurement of performance and the realization of improvement through management processes is therefore extended in the following section with the introduction of performance management.

2.3.3 *Integration of Performance Measurement into Management*

The measurement of performance constitutes improvement potential by quantifying the performance gap between an ideal and actual performance. The attainment

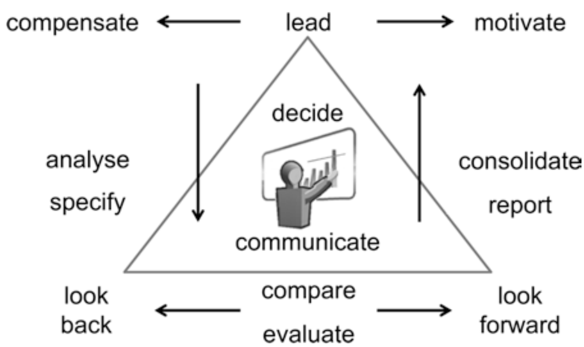


Fig. 2.18 Functions of performance measurement (Hon 2005)

of improvement to close the gap is in the responsibility of management (Lundberg et al. 2009; Folan and Browne 2005). Management can be defined as a process.

consisting of planning, organising, actuating and controlling, performed to determine and accomplish the objectives by the use of people and resources. (Terry 1968)

Accordingly, the management process encompasses four activities to initiate and adjust actions in order to realize a designated target (Mellerowicz 1963):

- Within the *planning phase*, methods and tools to achieve the target value are selected.
- The main task of the *organising phase* is to coordinate the resources ensuring the functioning of actions. This phase is combined in literature with the planning phase and aggregated as a joint phase (Grüning 2002; Günther 1991; Hilgers 2008).
- After the planning process has been completed, the implementation of actions is carried out constituting the actual progress towards achieving the target. This phase is therefore referred to as *actuating* or *directing*.
- In the final *controlling phase*, the outcome of actions is reviewed initiating control mechanisms, which steer the actions towards the designated target.

Taking a cybernetic perspective on management, the management process can fundamentally be understood as a control process, which strives to resolve problems in order to achieve and sustain an aspired, stable state (Gomez et al. 1975). The "science of control" is centred according to Wiener in the term *cybernetics* (Wiener 2000; Beer 1966). It belongs as a discipline to the theory of dynamic systems, which is concerned with the development of models based on systems as a conjunction of connected parts including their structures, interrelations and characteristics (Boulding 1956; Malik 2011).

The focus of cybernetics is on the control of systems and communication of information as a means to support the function of control (Otten and Debons 1970). The mechanisms enabling the control of systems are feedback and feedforward (see Fig. 2.19). Both inherit control strategies striving to abate the deviation from the desired target value enabling purposive actions and decision-making (Grüning 2002; Beer 1966; Mock 1986).

Feedback facilitates to reflect influences on the actual system state and to compensate the impact on the system in form of a negative information loop. In contrast, the concept of feedforward predisposes disturbances before they occur limiting the impact on the controlled system. The concepts jointly pursue the aim to support continuously the management process by adapting the input of the system (Mock 1986). Based on this perception, management is therefore considered as the "profession of control" (Beer 1966) and envisioned in form of a control loop.

In order to ensure an effective management control in practical applications, the adoption of the cybernetics approach demands information regarding the feedback and feedforward mechanisms affecting the dynamics and behaviour of the controlled system (Mock 1986). As a consequence, the central challenge to cybernetic

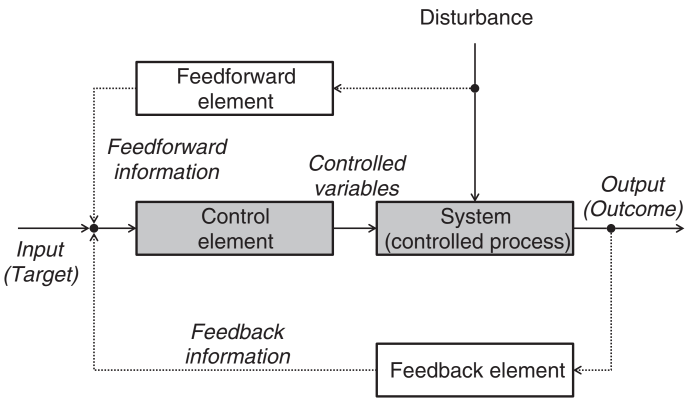


Fig. 2.19 Cybernetic control loops of management, adapted from (Grüning 2002; Baetge 1974)

management is to gain information in order to identify prevalent and evolving control mechanisms, which enable the attainment of the target value (Mock 1986).

Performance measurement can resolve this demand based on the results of the performance evaluation (Hilgers 2008). These enable to describe the effect of actions on the performance and therefore represent an important source of information, which can be used as input for the design of feedback and feedforward mechanisms (Hatry and Wholey 2006; Grüning 2002). Accordingly, performance measurement can be characterized as a means to specify management control as element of the cybernetic management process (Grüning 2002).

By actively using performance information within the control mechanisms, performance measurement is going beyond the evaluation of effectiveness and efficiency transitioning from the mere measurement towards management (Sturm 2000; Hilgers 2008). In accordance with the definition provided by Amaratunga and Baldry, performance management can be specified as

the use of performance measurement information to help set agreed-upon performance goals, allocate and prioritize resources, inform managers to either confirm or change current policy or program directions to meet those goals, and report on the success in meeting those goals. (National Performance Review 1997).

Given this definition, it is important to consider the dependence of performance management on performance measurement in an integrated context indicating the need for a performance management system (Folan and Browne 2005). Performance management systems comprehend methods and procedures in form of a framework ensuring the provision of relevant performance information to guide the management process towards the performance objectives (Krause and Mertins 2006). The common elements to plan, improve, measure and communicate performance as well as their interactions within a performance management system are illustrated in Fig. 2.20 showing the interrelations between the measurement and implementation activities.

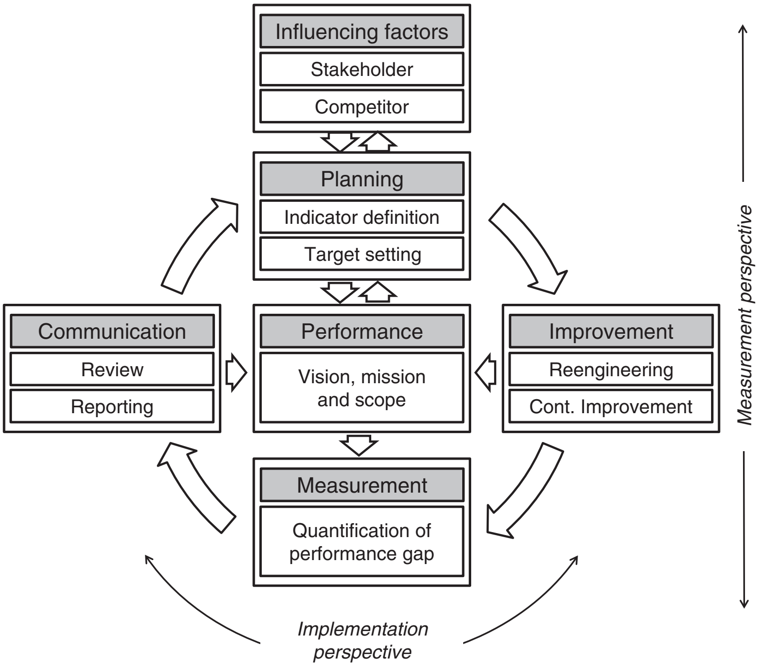


Fig. 2.20 Elements of a performance management system, adapted from (Krause and Mertins 2006; Hilgers 2008)

The illustrated activities of planning, improvement, measurement and communication form a self-learning process enabling progress through continuous improvement (Grüning 2002). Performance measurement and management can be seen in this management system as individual dimensions (Hilgers 2008). Both are connected to one another through the quantification of the performance gap. It embeds accordingly performance measurement as an element of management supporting the achievement of an initial target (Erdmann 2002).

2.3.4 Energy-Oriented Performance Management

The implementation and dissemination of performance management is advanced through a variety of particular economically and environmentally-oriented approaches representing individual frameworks to track the execution and pursue the improvement of activities (Folan and Browne 2005; Bourne et al. 2003; Neely et al. 2005). The approaches predominantly encompass monetary performance measures for strategic management levels as well as non-monetary measures on operational levels (Erdmann 2002; Dhavale 1996). The purpose of this section is to revise specifications of performance management systems for the energy usage in transformation processes providing methods and tools to quantify and bridge the energy efficiency gap of machine tools. This includes especially to differentiate the ambiguous term energy performance as well as to review means for the derivation of energy-oriented targets for performance measurement.

2.3.4.1 Energy Management System

Guiding the improvement of energy performance is a fundamental element of the recently published ISO 50001 on Energy Management Systems (International Standard Organization 2011). Originating from the ISO standards 9001 and 14001, the ISO 50001 bears a strong resemblance with the established management system standards. It can conjointly be integrated by organisations as part of an overall management system (International Standard Organization 2011). It defines a standardized framework of systems and processes enabling organisations to manage and enhance the energy performance (see Fig. 2.21).

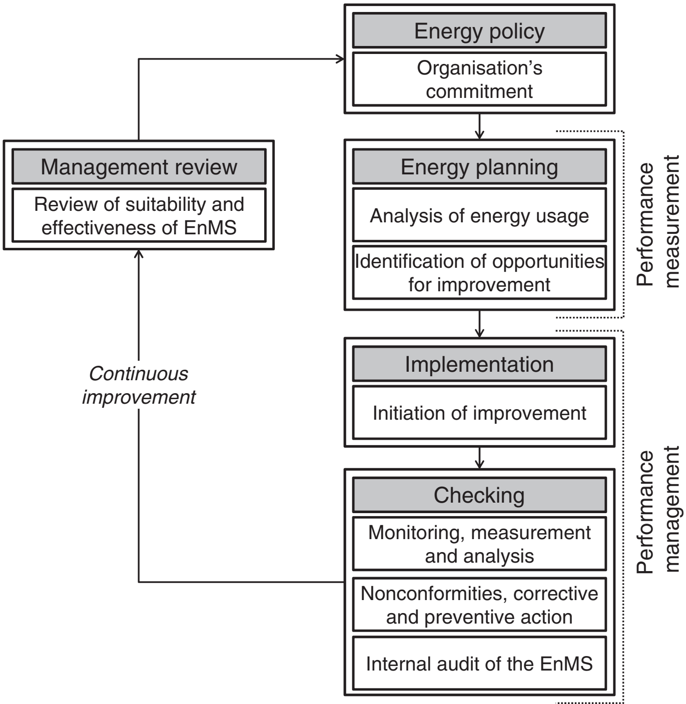


Fig. 2.21 Energy management system model, adapted from (International Standard Organization 2011)

Incorporating the elements of a performance management system, an energy management system (EnMS) encompasses the activities (International Standard Organization 2011):

- to implement an energy policy defining the organization's commitment,
- to perform an energy planning with the aim to identify and specify improvement potential,
- to initiate and implement improvement actions,
- to check the measurement and improvement of energy performance
- as well as to review the suitability and efficacy of the EnMS striving for continuous improvement of the management system.

With the definition of the mission, vision and scope of the EnMS, the energy policy corresponds to the initial element of the performance management system. Additionally, the energy planning complies with the activities of the performance measurement enfolding both the planning and measurement elements (see Fig. 2.20). It provides subsequently decisive information initiating the performance management in the implementation and checking activities.

By formulating the objectives and energy targets, the energy planning delineates the intention of the organisation and aspired commitment for improvement in energy performance. A prerequisite for transposing the objectives into measurable energy targets is however the specification of energy performance. According to the ISO 50001, energy performance comprehends "*measurable results related to energy efficiency, energy use and energy consumption*" (International Standard Organization 2011). It is consequently reflected through energy performance indicators representing quantifiable metrics (International Standard Organization 2011).

Energy efficiency is defined as the "*ratio or other quantitative relationship between an output of performance, service, goods or energy, and an input of energy*" (International Standard Organization 2011). Evading a distinct definition of the term, the ISO standard enumerates in the further course divergent examples as surrogates without any declaration of the underlying metrics. The lack of an unequivocal definition is also evident for the absolute energy performance indicators. It describes *energy use* as a "*kind of application of energy*" (International Standard Organization 2011) and *energy consumption* as the "quantity of energy applied" (International Standard Organization 2011).

With regard to the definition of an energy target as a measurable threshold for energy performance, the ISO standard refers to benchmarking as a methodological approach to gain quantitative input. In order to derive evaluative information about the achieved progress in energy performance, the EnMS proposes alternatively to compare the energy performance indicators with an energy baseline. Indicating a quantitative reference value of energy performance, the energy baseline is derived and updated through monitoring of energy demands in time studies (International Standard Organization 2011).

The preceding illustrates that the ISO 50001 uses main elements of performance management. It provides a general framework guiding the implementation of activities to pursue improvement in energy performance. Providing the basic structural elements of a management system, it does however not define distinct requirements for energy performance indicators and formalize methodological approaches for the design of energy performance targets (International Standard Organization 2011). An essential requirement for the implementation of an energy-oriented performance management remains therefore to decide on suitable indicators for the characterization of energy performance and means to derive energy targets.

2.3.4.2 Specification of Energy Performance Indicators and Energy Targets

Energy efficiency is an ambiguous energy performance indicator with a particular diversity of interpretations, which differ both in structure and in contextual form (Patterson 1996; Diekmann et al. 1999). Extending the examples provided in the ISO standard, a selection of applied energy efficiency indicators is compiled by Bunse et al. and Diekmann et al. in order to emphasize the wide scope of technical and economic variations (Bunse et al. 2010; Diekmann et al. 1999). An excerpt of identified metrics is comprised in Table 2.2.

Unifying characteristics among the ratios enable to differentiate classes of energy efficiency indicators in order to gain consistency among the various expressions (Diekmann et al. 1999). Patterson structures a first class of indicators for energy efficiency in form of dimensionless quantitative ratios (Patterson 1996). These can generally be subdivided into three segments reflecting the specific context of energy efficiency (see Table 2.3) (Patterson 1996; International Atomic Energy Agency et al. 2005). In line with the principles of thermodynamics, the first two segments designate ratios referring to the energy quantity and the energy quality. Defining the energy output relative to the total energy input, the scope of analysis for energy quantity concentrates on the transfer of energy in technical systems (e.g. electric motors). In contrast, the estimation of energy efficiency with

Table 2.2 Excerpt of energy efficiency indicators, based on (Bunse et al. 2010; Diekmann et al.1999; Patterson1996; Neugebauer et al. 2010)

Indicator	Characterization
Conversion efficiency	Energy output per energy input
Degree of efficiency	Net energy per used primary energy
Energy consumption intensity	Energy consumption per physical output value
Energy efficiency	Useful output per energy input
Energy efficiency factor	Process energy demand per machine energy demand
Energy intensity	Energy demand per unit of industrial output
Energy productivity	Output quantity per energy input
Final energy efficiency	Energy savings by the same benefits
Specific energy consumption	Energy demand per tonne of product material
Specific power consumption	Power consumption at a working point (or avg. of a cycle)
Thermal energy efficiency	Energy value available for process per unit energy value

Table 2.3 Classification of performance indicators for energy efficiency, adapted from (Patterson 1996)

Classes of energy efficiency indicators	Segments	Ratio	Units
Dimensionless quantitative rations	Thermodynamic (Energy quantity)	$\frac{\text{Useful energy output}}{\text{Total energy input}}$	[-]
	Thermodynamic (Energy quantity)	$\frac{\text{Actual energy input}}{\text{Ideal energy input}}$	[-]
	Economic	$\frac{\text{Economic quantity value}}{\text{Energy input costs}}$	[-]
Energy intensity (EI)/ specific energy consumption (SEC)	Physical-Thermodynamic	$\frac{\text{Energy input}}{\text{Physical quantity value}}$	e.g. [J/g]
	Economic-Thermodynamic	$\frac{\text{Energy input}}{\text{Economic quantity value}}$	e.g. [J/€]

regard to an ideal energy limit is concerned to assess the quality of energy conversion. A third segment of energy efficiency indicators encompasses monetary valued ratios, which are primarily used to illustrate aggregated data about economic activities (Diekmann et al. 1999).

Despite the dimensionless indicators, the energy intensity (also defined as specific energy consumption) describes a second class of performance indicators for energy efficiency (see Table 2.3). Relating the energy demand to a numerical quantity value, the energy intensity emphasizes explicitly the usage of energy to conduct a transformation (Diekmann et al. 1999). Generally, physical and economic characterizations are observed to define energy intensity.

Revising the composition of the indicators, it becomes apparent that only the ideal energy demand of the energy quality indicator instantly provides an evaluative reference for energy efficiency. In contrast, all alternative performance indicators rely on the comparison with defined reference thresholds or the monitoring of relative changes to evaluate progress and the achievement of targets (Patterson 1996; Erlach and Westkämper 2009).

As a means to derive thresholds for energy targets, the Methodology study for Ecodesign of Energy-using Products (MEEUP) designates an alternative approach to evaluate the performance of energy-using products through comparative assessment (Tanaka 2008; Kemna et al. 2005). This methodology is applied in the context of the Ecodesign directive initiating energy performance regulations to improve the environmental impact within energy-related product categories (Kemna et al. 2005; European Parliament and Council 2009). To conduct a comparative assessment according to the MEEUP, the development of an individual evaluation procedure is required for each product category under study. The empirical comparison relies additionally on market available products requiring therefore to select representative entities within the evaluated product category. Defining particular test cycles and real-life operating conditions, the energy demands within the product group are assessed enabling the identification of best available solutions for the given evaluation procedure (Kemna et al. 2005). This approach has for instance been successfully adopted for electric motors (de Almeida et al. 2008).

The ideal energy demand of the thermodynamic indicator and the comparative assessment represent in conclusion two approaches to define unbiased energy targets for energy performance management. While the thermodynamic indicator defines a theoretical, unattainable energy target, the comparative assessment enables to cope with this limitation by finding best available solutions. However, this approach is challenged with the definition of a functional unit for comparison, the availability of comparable systems and the time demand to conduct the assessment (Kemna et al. 2005).

2.3.5 Findings

The pursuit of ecological sustainability through efficiency is considered as the most cost-effective and immediate strategy to reduce the demand of resources and associated emissions of activities. The adoption of the strategy to improve the energy demand of transformation processes raises the issue to quantify the actual and ideal energy performance in order to uncover the attainable potential for energy-related improvement. The quantification of improvement potential constitutes an integral element of (energy) performance management providing a consistent framework to derive information about the performance of activities and implement control mechanisms to pursue progress.

Revising the existing specifications and implications of energy performance, the following conclusions are drawn:

- Energy performance is an ambiguous term, which cannot be framed in one single, ideal indicator.
- The design and formulation of precise and verifiable indicators demands to consider the specific focus and purpose of the analysis as well as the context of the application.
- The specification of energy intensity as an energy efficiency indicator appears to be favourable for transformation processes underlining the usage of energy to pursue value creation.
- The setting of an ideal energy performance target remains the most critical aspect to retain the thrust towards improving the performance and bridge the performance gap. Yet, it is the fundamental element to trigger improvement.
- The measurement of performance and the target-oriented realization of improvement through management represent two elements conjointly forming a comprehensive energy performance management.

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