Energy Efficiency Measures for the Design and Operation of Machine Tools: An Axiomatic Approach

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Abstract

Due to environmental legislation and increasing customer demand, the development and deployment of energy-related improvement measures for machine tools has intensified. These measures centre different aspects of machining as integrating energy efficient components or applying start-stop strategies. Although the measures aim for a reduction of energy demand, guidance on the selection and prioritization of efficiency measures is necessary in order to identify adequate methods and create awareness about the effects and interdependencies. Using axiomatic design a matrix is developed that relates functional requirements of improving energy efficiency of machine tools to design parameters.

Keywords:

Machine Tools; Energy Efficiency; Axiomatic Design

1 INTRODUCTION

The reduction of electrical energy demands in the use phase of machine tools is an essential key to improve the environmental performance over the entire life cycle. Preliminary environmental studies for machine tools used in discrete part manufacturing (e.g. turning and milling) indicate that a proportion of more than 99% of the environmental impacts is due to the consumption of electrical energy [1]. As a consequence, the improvement of the environmental performance of machine tools is enforced by European environmental legislation through the preparatory initiation of an ecodesign-directive and moreover approached by self-regulatory initiatives of the machine tool industry [2, 3].

Measures to improve energy consumption of machine tools provide substantial leverage to reduce the associated environmental impacts in the use phase. The development of those measures comprises organizational as well as technical aspects. While organizational measures focus on the mode of operation of a machine tool, technical measures for instance address specifically the substitution of components through energy efficient alternatives. Although all measures are determined to improve the energy consumption, a systematic concept that provides structured guidance for the implementation of energy efficiency measures and associated impacts is yet absent. Based on the initial functional requirement to reduce the energy consumption for a machining cycle and in accordance with the axiomatic design theory, a decomposition matrix is developed which decomposes functional requirements and design measures for improving energy efficiency of machine tools. The proposed concept intends to successfully guide the implementation of energy efficiency measures for machine tools.

2 IMPLICATIONS OF THE ECODESIGN DIRECTIVE ON MACHINE TOOLS

The ecodesign directive provides an EU wide framework that defines ecodesign requirements for products which either directly (energy-using) or indirectly (energy-related) impact the environment through the consumption of electrical energy in the use phase of the life cycle [4]. The directive is applicable for products which can be characterized by the following three criteria. Products should have significant sales and trade relevance with more than 200.000 units sold in the EU per year, considerable environmental impacts due to the use of energy (anticipated as 1000 PJ of primary energy) and a notable potential for improvement in terms of its environmental impact without entailing excessive costs [2].

As a result of the initiation of an ecodesign directive, rules and criteria are determined that limit the energy demand of products made available to markets in the European Union. Moreover, rating schemes can be defined that classify products according to the energy efficiency. An example therefore is the energy efficiency rating for electrical motors which evaluates the energy efficiency through relating mechanical output power to electrical input power in defined performance test procedures [5].

Preliminary studies which elaborated the extension of the ecodesign directive to new product groups estimated the associated environmental impacts of machine tool usage and pointed out the existence of eminent improvement potential. Within the analyzed product groups, machine tools ranked third place with a primary energy demand of 17.475 PJ per year [6]. In addition, promising saving potentials have been identified as improving the power factor, reducing the power demand in idle mode as well as integrating variable speed drives [6]. As a consequence of these preliminary studies, the implementation procedure described by the ecodesign directive was opened in 2008 aiming at the improvement of the environmental performance of machine tools and commenced with the initiation of a machine tool related product group study in 2010. Triggered by these efforts and industry self-regulatory initiatives, the development and deployment of energy-related improvement measures have further intensified starting, for instance, from the development of energy efficient components to the integration of energy-management principles into machine tool controls [1]. Prior to the analysis of improvement measures, the associated energy demand of machine tool operation is described in order to derive the objectives and scope for the axiomatic decomposition.

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3 ENERGY EFFICIENCY OF MACHINE TOOLS

3.1 Power Demands of Machine Tools

Machine tools represent stationary assemblies that are fitted with (or intedend to be fitted with) a drive system other than directly applied human effort. They consist of joined parts and moving components enabling the entire machine tool to perform a complex, useful function which is the geometric shaping of workpieces made of arbitrary materials using appropriate tools and technologies [7, 8].

In machine tools electrical energy is transformed into mechanical or other desired forms of energy. The energy consumption of a machine tool results from the temporal accumulation of the individual power demands for each component (see Figure 1) [9]. Thus, the power demand is not static but rather dynamic throughout the machine tool operation. It is influenced by the design of the process and the selected machine tool configuration.

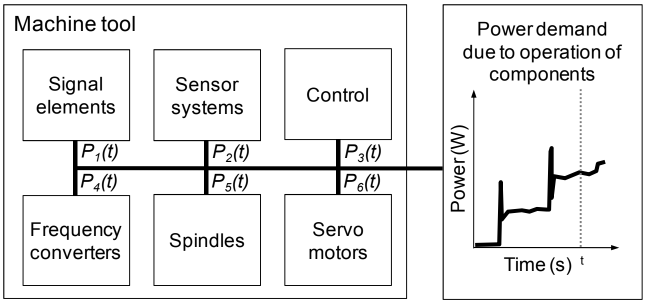

Figure 1: Agglomeration of power demands - according to [9, 10].

Power meters enable to capture the dynamic power demand of a machining process which consequently provides a basis to recognize actions and associated power demands. Reviewing the power profile of an exemplary internal cylindrical grinding process in Figure 2, the start-up of the machine tool and spindle as well as two machining processes with varying material removal rates (MRR) can be determined. Based on the resulting power demand, a variable and fixed portion can generally be differentiated [11, 12]. While the fixed power covers the constant demand, which is necessary to ensure a functional mode of operation (ready for operation), the variable demand power considers the power for carrying out the machining operation without touching the work piece (so called air-cut) and the material removing capacity [13].

In this case, the power measurement for the grinding machine shows that more than 3.5 kW are required as fixed demand and that the power demand increases up to 5.2 kW throughout processing including the variable power demand. These power demands do not consider the power demand of the mandatory filter unit which is providing coolant to the machine and continuously operating. However, the power profile enables to evaluate machining processes with regard to their energy demand [14]. The two displayed grinding processes differ only in the value of the MRR and are given in Table 1. The processing times and energy demands are derived from the data of the power measurement; initially considering the activation of the spindle to the final stop of the spindle for each process. The results show that the 1^{st} process with higher MRR prevails in terms of energy consumed per removed material. If the energy demand is allocated to the removed material volume and processing time, the resulting specific energy demand for the processes decreases with reduced MRR.

	1^{st} Processing	2^{nd} Processing
Processing time (s)	121	246
Total energy (Wh)	321	482
- Fixed energy (Wh)	110	253
- Variable energy (Wh)	211	229
Material removed (mm^3)	3600	3600
Total energy per removed material (Wh mm^{-3})	0.089	0.134
Specific energy (Wh mm^{-3} s^{-1})	0.00074	0.00054

Table 1: Comparing machining processes according to the energy demands.

With regard to the total energy demand for a machining process, optimization measures should aim at maximizing the MRR in order to reduce the impact of the fixed power. However, while increasing the MRR it is also absolutely essential not to neglect the resulting process conditions and work piece quality.

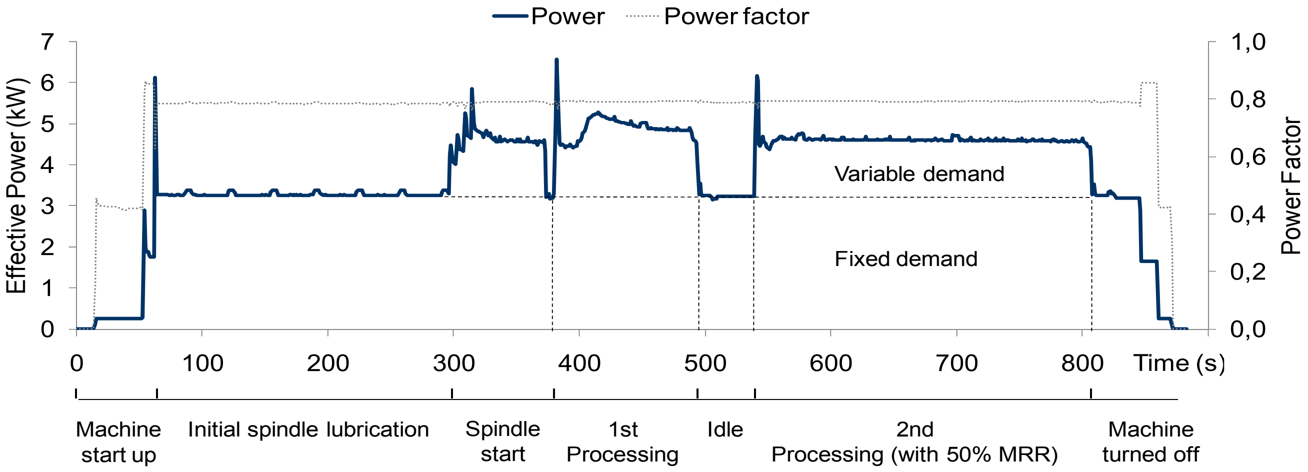

Figure 2: Power demand of a grinding machine (two processing cycles).

In addition to the power demand, Figure 2 also displays the power factor which indicates how efficiently the machine tool is using the power supplied to it [15]. While the power factor generally remains at 0.8 in the example of the grinding machine, the start-up and shutdown of the machine tools leads to power factors less than 0.5. Thus, only 50% of the power supplied is used as effective power.

With regard to the power demand and power factor resulting from the operation of the grinding machine tool, the indicated saving potentials given in the EU directive can easily be identified. This includes the improvement of the low power factor and most importantly the reduction of power demands in non-processing times (e.g. reduce fixed power during spindle lubrication and in idle mode). Although saving potentials can be determined to improve the energy consumption, a systematic concept that provides structured guidance for the selection and implementation of energy efficiency measures and the associated impacts is yet absent.

3.2 Classification Scheme to Improve Energy Efficiency of Machine Tools

In general, energy efficiency is defined as relation of output to energy input. Energy efficiency can furthermore be specified using a variety of indicators based on physical, economic or thermodynamic reference parameters [16]. Due to the complexity of defining a functional reference for machine tools, an overall indicator for the valuation of energy efficiency of machine tools is yet obsolete [1]. Thus, as a basis for deriving improvement measures the energy efficiency of machine tools is in this paper described as the amount of electrical energy invested to perform a complete machining operation consisting of the procedures start-up, set up, processing of a distinct amount of material and shut down (as displayed in Figure 2).

Consequently, improving energy efficiency for the above mentioned scope requires either maximizing the output for a given input or minimizing the energy required to provide a given output. In the case of machine tools, the minimization of energy is encompassed by improvement measures that initially reduce energy demands and subsequently reuse invested energy or finally recover energy losses of transformation processes [according to 17].

Reducing energy consumption

With regard to the power demand in Figure 3, a reduction of energy consumption can directly be achieved by technical measures that reduce the power demand of components through applying energy efficient devices. In addition, the enhancement of energy efficiency can indirectly be realized through organizational measures [18]. While technical measures include for instance the replacement of hydraulics and motors with energy-efficient ones, organizational measures focus on the optimization of process times based on energy-oriented process planning (compare Table 1).

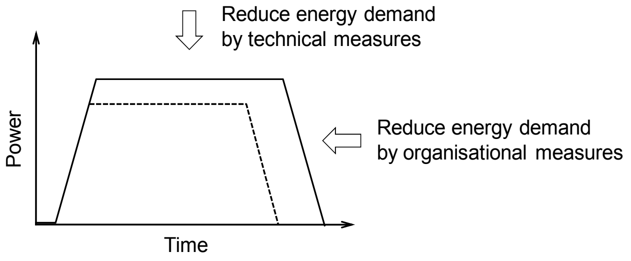

Figure 3: Strategies to reduce the energy demand of machine tool usage [according to 19].

Reusing invested energy

Apart from the reduction of energy consumption, improvement measures can furthermore aim at reusing energy. Especially motors enable to reuse energy once the motor acts as a generator in braking mode. Examples include for instance the energy balancing of multi-motor drives or kinetic buffering of energy [20].

Recovering energy

Apart from the consideration of energy consumption, another important aspect is the conversion of electric energy within the machine tool and the resulting energy liberation. Recovering energy losses through heat recuperation techniques may be beneficial once a heat potential is present. Energy recovery potentials are generally approached by thermal management (e.g. apply heat exchanger to control cabinets) [1, 21].

In addition to the effect of an improvement measure, the point of action can be classified according to the process, specific components or the entire machine tool design. Hence, this classification takes into account the implementation ability of the measure. While a process optimization can be applied instantaneously, changes in the design of the machine tool are more beneficial for the subsequent machine tool generation.

Based on this classification scheme, every improvement measure can be clustered and prioritized according to the effect and the implementation ability. Thus, this builds the basis for the subsequent decomposition of saving potentials and interlinking with adequate measures.

3.3 Improvement Measures

Triggered by the necessity to improve the environmental performance of machine tool usage, measures to minimize the energy demand of machine tools in the use phase have been developed and deployed. Initially, a catalogue of measures has thus been established based on the available measures developed and collected within the research project Prolima, the initiative Blue Competence as well as the self-regulatory initiative lead by Cecimo [1, 22, 23].

All in all, a set of more than 190 improvement measures has been listed and classified according the developed classification scheme. It has to be pointed out that not all measures are categorized excluding those which do not provide an energy-related effect. Hence, in Figure 4 the selection of measures which could clearly be assigned to the given set of categories is displayed.

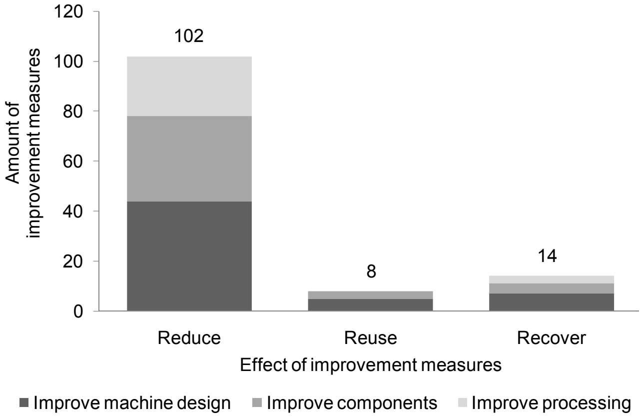

Figure 4: Classification of energy-related improvement measures.

Based on the classification, the relevance of measures to reduce the energy consumption was determined. Although more than 40% of these measures aim at reducing the energy demand through improved machine tool design, 22% of the measures are pursuing the same effect by improved process design.

As a result of the classification, more than 100 energy-reducing measures have been identified. However, due to couplings and interrelations between the measures and the resulting effects on the energy consumption, a systematic concept is required that provides structured guidance for the selection and implementation of energy efficiency measures. Thus, a design guide is developed with regard to axiomatic design theory which decomposes improvement measures as design parameters to fulfill the functional requirements (representing saving potentials).

4 DECOMPOSITION OF ENERGY EFFICIENCY MEASURES TO IMPROVE MACHINE TOOLS

4.1 Axiomatic Design

Axiomatic design is a systematic tool that structures and clusters measures within a design process through mapping of functional requirements and design parameters. A functional requirement (FR) can be defined as a set of functional needs of a system (e.g. product or process). A related design parameter (DP) represents a response which fulfills the FR, hence leading to a structured design process [24, 25].

The relationship between FR and DP is defined in a vector which displays the decomposition of the FR with unique and preferably uncoupled DP. The decomposition has for that reason to consider two axioms in order to obtain an optimal design process [24]:

1. Independence Axiom: Maintain the independence of the functional requirement.
2. Information Axiom: Minimize the information content.

In accordance with the axiomatic design theory, the decomposition demands to define an initial FR which states the objective and scope for the design process. At the main decomposition level, the related DP is rather extensive and will lead with ongoing decomposition to more specific and detailed solutions that fulfill the requirements [26].

Hence, the axiomatic design methodology enables to link energy saving potentials for machine tool usage with optimal improvement measures. Moreover, by ordering the results in a systematic top-down structure and integrating path dependency (reading from left to right) the decomposition vector provides guidance for the implementation of measures to minimize the energy demand of a machining cycle (according to [27]).

4.2 Objective and Scope

With regard to the definition of energy efficiency, the objective of the decomposition focuses solely on the minimization of the electrical energy demand to perform a machining cycle. Moreover, the scope is limited to a machine tool with its integrated components; disregarding additional peripheral devices as coolant filter systems.

In contrast to the use of indicators like the specific energy consumption or energy per manufactured part, the scope is set to cover the power demand of a full machining cycle without additional references. This enables to consider the characteristic energy consumption of a machine tool with value-adding and also non-value-adding activities (e.g. idle mode). Moreover, this rather extensive focus avoids considering the product material and processing technology specifications.

4.3 Mapping of Functional Requirements to Design Parameters

The energy efficient machine tool decomposition focuses solely on energy-related objectives and thus the contribution of FRs on minimizing the energy demand. The resulting FR and DP of the initial decomposition are displayed in Table 2. Based on the initial FR 1, the subsequent level resolves the three FRs to reduce, reuse and recover energy with the DP to analyze specific saving potentials to fulfill the requirements.

To extend the decomposition, the branch of the FR 11 (minimize energy) is decomposed into FRs aiming at the reduction of machining time (FR 111) prior to reducing the power demand of components (FR 112). While the machining time involves organizational measures based on energy-aware process planning, the FR 112 can be fulfilled by technical means to avoid or reduce the power demand of energy using components.

FR 1: Minimize energy demand of a machining cycle
DP 1: Energy efficient machine tool decomposition
FR 11: Reduce energy input
DP 11: Identify and explore potentials for energy reduction
FR 111: Minimize operation time of machining process
DP 111: Energy-oriented process planning
FR 1111: Minimize processing time
DP 1111: Perform process at maximum material removal rate ensuring target quality
FR 1112: Minimize time of non-value adding tasks
DP 1112: Reduce time non-value adding tasks
FR 11121: Avoid non-value adding tasks
DP 11121: Eliminate non-value adding tasks
FR 11122: Reduce time of non-value adding tasks
DP 11122: Plan process with minimal non-value adding tasks
FR 112: Minimize power demand of a machining cycle
DP 112: Improve power demand of the machine tool
FR 1121: Operate components efficiently
DP 1121: Use components only when required
FR 1122: Minimize power demands of components
DP 1122: Substitute inefficient components with efficient ones
FR 1123: Minimize power demand to operate machine
DP 1123: Reduction of moved masses
FR 12: Reuse energy
DP 12: Identify and explore potentials for energy reuse
FR 121: Ensure energy feed back
DP 121: Integrate energy feed back system
FR 1211: Reuse kinetic energy to power the machine tool
DP 1211: Feed back the braking energy to power the machine tool
FR 1212: Conserve kinetic energy
DP 1212: Integrate kinetic energy buffering systems
FR 1213: Maximize energy potential
DP 1213: Transform energy into other useful forms
FR 13: Recover energy losses
DP 13: Identify and explore potential energy losses
FR 131: Ensure efficiency of energy transformation
DP 131: Eliminate non-efficient transformations
FR 132: Minimize energy losses of transformation
DP 132: System to prevent and minimize losses
FR 133: Maximize energy recovery
DP 133: Integrate energy recovery system
FR 1331: System to directly recover electrical energy
DP 1331: Apply thermal management to recover electrical energy
FR 1332: System to indirectly recovery energy
DP 1332: Apply thermal management to conserve energy losses

Table 2: Derived FR and DP of the energy efficient machine tool decomposition.

The decomposition of the branch FR 12 shows just one direct link to reuse energy of accelerated or differently powered components which could be satisfied by applying feed back or buffering measures.

In contrast, the third branch of FR 13 entails three major FRs. Based on the second law of thermodynamics, the recovery of energy has to ensure that transformation of electrical energy is done efficiently, hence avoiding the losses in first place (FR-DP 131). Based on this, the inevitable losses should be minimized (FR-DP 132) before the application of recovery measures is considered (FR-DP 133).

In alignment with the classification of improvement measures in Figure 4, the decomposition of FR and PD displayed in Figure 5 confirms the increased availability of improvement measures to reduce the energy consumption of machine tool usage in contrast to reusing or recovering energy. With regard to improving the energy demand of a machine tool, this initial decomposition enables to identify and structure potentials and improvement measures guiding the successive deriviation of implementation sequences.

5 SUMMARY

Against the background of the increasing availability of energy-related improvement measures for machine tools, this paper presented axiomatic design as a systematic tool to structure improvement potentials and provide guidance for the optimal implementation sequencing of measures. Based on the initial functional requirement to minimize the energy demand of a machining cycle, design measures are derived aiming at the reduction, reuse or recovery of energy. Based on the first decomposition, the decomposition vector will be detailed in future work and extended in detail to describe the couplings and interrelation between the FR and DP.

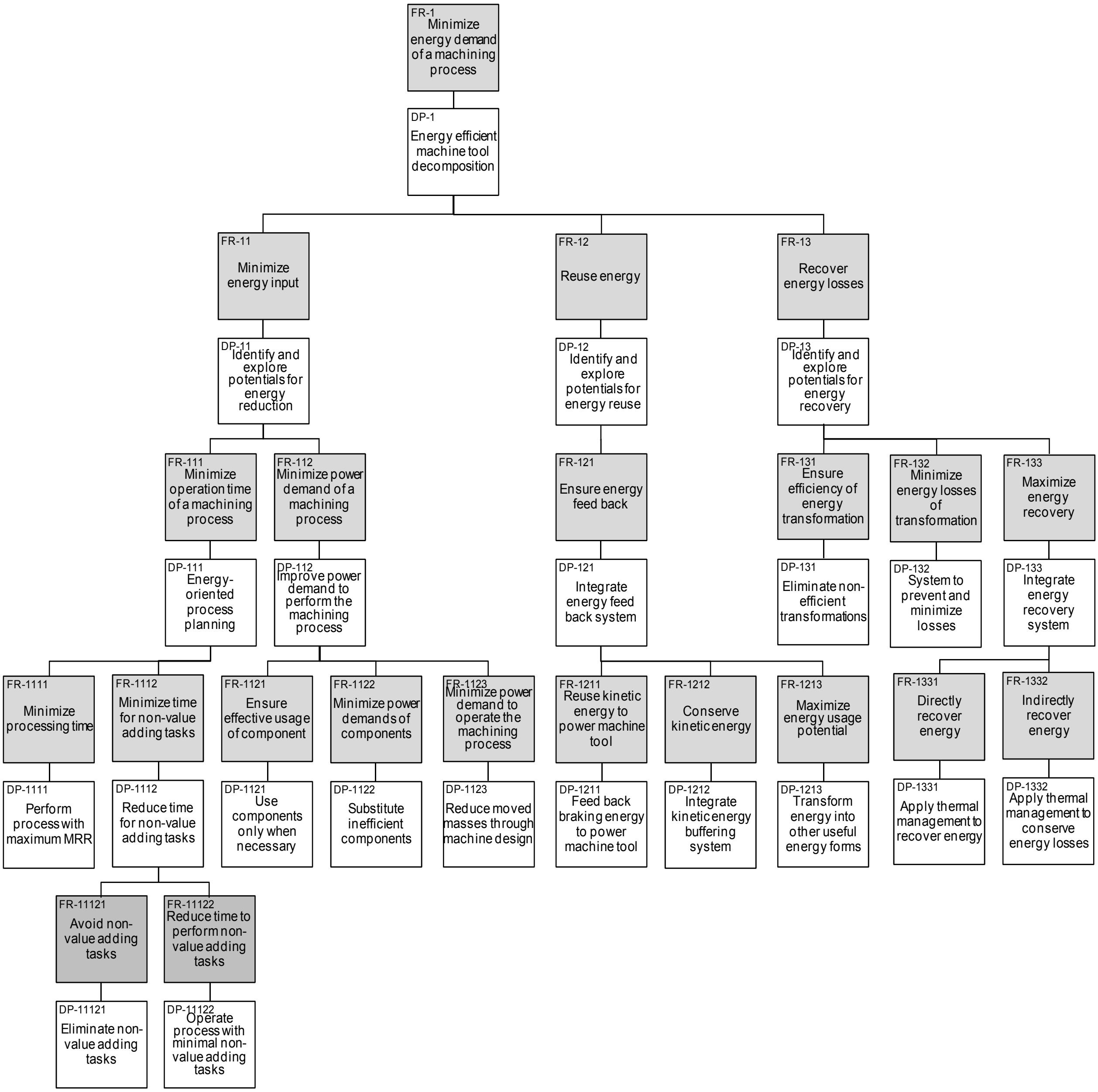

Figure 5: The first 4 levels of the energy efficient machine tool decomposition.

6 ACKNOWLEDGEMENTS

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