REVISED 25 JUNE 2018

Machine tools: 12 points – catching complexity in ecodesign

Tim Hettesheimer
Fraunhofer Institute for Systems and Innovation Research ISI
Breslauer Strasse 48
D-76139 Karlsruhe
Germany
Tim.Hettesheimer@isi.fraunhofer.de

Clemens Rohde
Fraunhofer Institute for Systems and Innovation Research ISI
Breslauer Strasse 48
D-76139 Karlsruhe
Germany
Clemens.Rohde@isi.fraunhofer.de

Paul Waide
Waide Strategic Efficiency
4 Winster Avenue
Manchester M20 2YG
UK
paul@waide.co.uk

Keywords

ecodesign, case studies, assessments, machine tools, points system

Abstract

The saving potentials from the adoption of appropriate Ecodesign technologies have been shown to be significant; however, due to the increasing share of complex products or product systems in the Ecodesign work plan, the process of deriving prospective Ecodesign and Energy Labelling requirements is becoming progressively more challenging. Such complex products, as for example machine tools, are characterized by a high degree of heterogeneity and multiple functional units. A machine tool can thereby be defined as a fixed powered tool for cutting or shaping metal, wood, or other material. This could be for example a simple and small lathe or drilling machine as well as a large-scale and highly automated multi-spindle machine, which combines various technologies in one. In order to assess these complex products with regard to their potential benefits from Ecodesign and Energy Labelling requirements, this paper proposes a "points-system" based methodology that could be applied to the development of Ecodesign requirements for complex products and/or product systems. This approach has been elaborated for the European Commission within a technical assistance study. The starting point was a review and assessment of existing methods (for example LCA ISO 14040 and 14044, STRES, BREEAM, LEED, …) and their potential applicability for adaptation and use in the appraisal of Ecodesign requirements for complex products. Based on the findings a generic method consisting of 9 steps was developed. After defining a generic Ecodesign points-system approach for complex products the methodology was applied to the specific case of machine tools. This case is especially challenging, not only because of the complexity of the products but also because of the problem of defining a suitable reference system as benchmark. So far, some attempts have already been made without fully meeting the requirements for a reference system. This paper demonstrates a methodological approach which enables this basic problem to be solved and a reference system defined regardless of the complexity of the specific machine tool being addressed. The methodology is applied to hypothetical machine in order to illustrate it. The main insights from this evaluation process and shared before the paper closes with a discussion of the benefits and boundaries of a "points system" approach for machine tools.

Introduction

This paper is based on the findings of a project initiated by the European Commission to evaluate and derive a methodology for a points system that could be used in the development of eco-design requirements for complex products and/or product systems. This need arises from the increasingly frequent study of more complex energy-related products and systems for prospective eco-design and energy labelling specifications carried out in the framework of the Ecodesign work plan. This includes, for example, machine tools, data storage devices and professional washing machines/or driers.

Complex products are characterized by the fact that they may have more than one functional unit due to the variety of functions that the product can perform, or that functional units may be difficult to assess due to measurement or methodological difficulties. Furthermore, it is common for the product groups concerned to exhibit different heterogeneities, which makes it difficult to assess them against common metrics and measurement methods. However, since the savings potentials for the use of appropriate eco-design technologies can be significant and theoretically these technologies can be evaluated in a modular manner, the European Commission has been interested in examining whether it is possible to develop an assessment methodology for product systems from technology/design modules that takes into account the ensemble of modular technologies used.

This thought was first explored in the context of the Ecodesign process for machine tools in a working document presented by the Commission at the Consultation Forum in May 2014, which proposed a possible option-based points system approach (European Commission 2014). The resulting discussion highlighted the potential of this concept, but also the need to explore options in greater depth and develop a rationale for identifying viable approaches and assessing their strengths and limitations. The project reported in this paper, aimed to resolve this problem by carrying out analyses that clarify the options, identify the most promising method (s) and then demonstrate their feasibility by means of some case studies. In this context the case of machine tools was revealed to be especially difficult to assess. The reason for this is due to their high level of complexity and heterogeneity because of their varying areas of applications and sizes. Under these circumstances, a reference machine tool can hardly be defined. However, this paper describes a methodological approach that allows a reference system to be defined, despite these challenging circumstances, that allows a points-system based approach to be applied to the case of machine tools. It also highlights its limitations and where further research activities are needed. The paper follows the generic points-system methodology developed within the project as described in section 2 before presenting the case study for machine tools in section 3. Finally, section 4 provides a discussion of the approach developed and gives an outlook for further activities.

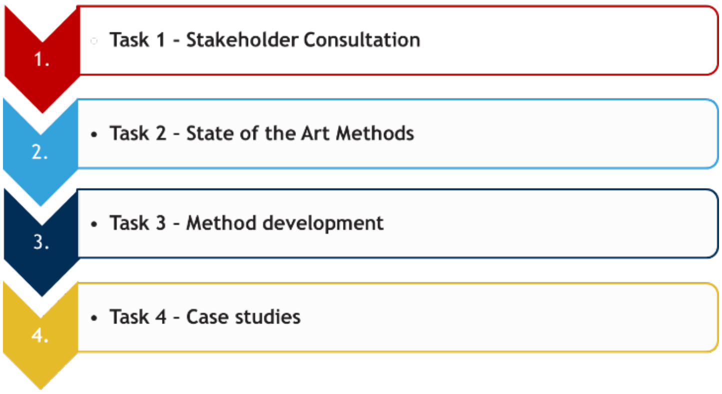


Figure 1. Overview of the four main tasks for developing a points system.

Methodological approach and development of a points system

In order to develop a points-system methodology, four main tasks were conducted, which are summarised in Figure 1.

As previously stated, this paper focuses on the special case of machine tools and the key problem of defining a reference system. For this reason, the paper is focused on reporting the Task 4: Case studies work. Nevertheless, it is also important to understand the whole concept of the methodology. For this reason, the preceding three tasks are also briefly described.

TASK 1 – STAKEHOLDER SURVEY

The stakeholder consultation process was very important to enable the compilation of technical and procedural input and to gather relevant views on the acceptance of the concept, the most appropriate approaches and the feasibility of the methods developed. It is also an important tool to facilitate the dissemination of study activities and results. Therefore, a survey of stakeholder views was conducted (see Waide 2017a).

TASK 2 – REVIEW OF STATE-OF-THE-ART METHODS IN WHICH RELEVANT EXISTING METHODS ARE CATALOGUED AND REVIEWED, FOLLOWED BY A COMPARATIVE ANALYSIS

This task entailed a review of state of the art methods used to assess the environmental impact of complex and multi-level criteria systems. In particular, it describes and assesses a variety of multi-criteria environmental impact assessment methodologies and points-system based decision models to examine their properties and assess their potential applicability for adaptation and use in the assessment of Ecodesign requirements for complex products. Within this review the schemes in Table 1 were evaluated.

The methods were evaluated within a comparative assessment framework that included assessments against the following criteria: effectiveness; accuracy; reproducibility; enforceability; transparency; ease and readiness of application; and capacity to be implemented within the legal, procedural and analytical rubric of the Ecodesign and Energy Labelling Directives.

The results of this review and subsequent consultations with stakeholders revealed that the majority of stakeholders didn't consider any of these methods, even allowing for modification, as suitable for Ecodesign applications. Rather, the conclusion was that any appropriate points-based methodology would need to be developed in a way that is informed by the experience of these other multi-criteria evaluation methods. This results in the derivation of the generic methodological approach that was explained and discussed in the Task 3 report (summarised below) and subsequently applied in the case studies dealt with in Tasks 4 and 5 of the study.

The evaluation revealed, that since most of these methods have not been developed with the Ecodesign regulatory process in mind, they are not directly adapted or applicable to its use. However, they share many elements that are useful in carrying out Ecodesign-like assessments. Apart from two exceptions (the ISO 14995-1, energy-efficient design methodology for machine tools and the EU Energy Label for space heating systems), the methods do not offer an approach tailored to managing complex functional units in which one and the same com-

Table 1. List of multi-criteria assessment concepts (see Peeters et al 2017).

Points system	Assessment area	Short explanation
ISO 14040 and 14044	Life cycle assessment principles, framework and guidelines	International standards on Life cycle assessment, principles and framework (ISO 14040) and requirements and guidelines (ISO 14044).
Product Environmental Footprint (PEF)	Multi-criteria environmental impact life cycle assessment of products	PEF is a Life Cycle Assessment (LCA)-based method to calculate the environmental performance of a product. The method was developed by the European Commission's Joint Research Centre and is currently being tested in a pilot phase.
Field trial of environmental labels in France	Multi-criteria environmental impact life cycle assessment of products	A labelling trial to supply full life cycle environmental impact information using a multi-criteria approach.
Common framework of core performance indicators for resource efficiency assessment in the building sector	Multi-criteria environmental impact assessment of buildings	A common framework of indicators to assess the sustainability of buildings being developed by the European Commission.
Material based environmental profiles of building elements (MMG)	Multi-criteria environmental impact life cycle assessment of building elements	Methodology and database for life cycle assessment of building elements.
Methodology to integrate cost effectiveness in determining the performance of a technology in the framework of Strategic Ecological Support (STRES)	Multi-criteria environmental impact life cycle assessment of investments	Methodology to determine the cost effectiveness of an environmental or energy-related investment.
Environmental impact assessment – Hybrid LCA methodology	Multi-criteria environmental impact life cycle assessment of goods, processes and services	Hybrid conventional LCA methods and input-output economic modelling for more comprehensive and rapid LCA analysis.
BREEAM	Environmental assessment of buildings	System originates in UK, but used all over the world. Designers have to achieve a certain numbers of points related to concepts and efficiency/design factors, in order to claim certain design levels.
LEED	Environmental assessment of buildings	System originates in US, but used all over the world. Designers have to achieve a certain numbers of points related to concepts and efficiency/design factors, in order to claim certain design levels.
DGNB	Environmental assessment of buildings	German system for the sustainability evaluation of construction projects.
ISO 14955-1: Machine tools	Energy efficiency of machine tools	A methodology for the design of energy efficient machine tools.
Points system Machine Tools	Ecodesign of complex products	Option of ranking machine tool energy in use performance via a points system inspired by the BREEAM system for buildings.
AHP technology portfolio assessment techniques	Multi-criteria evaluation framework applied to technology investment decisions	AHP-type hierarchical decision modelling applied to multi-criteria assessments of technology investment portfolios in businesses.
Points systems used for eco-labelling	Multi-criteria environmental impact evaluation framework	Examination of Ecolabelling systems and relation to points systems.
Points systems used for green public procurement	Multi-criteria environmental impact	Examination of Green public procurement systems and the use of points systems in procurement.
The EU "installer energy label" for heating systems	Energy labelling of complex products	Applies an extended product approach to develop a heating systems energy label.
The Europump Extended Product Approach	Ecodesign for complex products	Applies an extended product approach to develop Ecodesign proposals for various pump systems.
Ecodesign Lot 37 lighting systems investigation	Ecodesign of complex products	A methodology which considers the product scope as a holistic system.

ponent has more than one function. However, the ISO 14995-1 standard makes this easier by providing a detailed illustration and assignment of functionality to product subsystems for the specific case of machine tools. The same applies to the energy label for space heating components, which can offer both room heating and hot water production.

Furthermore, although the listed methods are used in different applications, similarities are observed between many of them:

- About half of them are pure points-system methods and the other half are methods that could be adapted for use as potential components within a points-system.
- About half of the methods include a classification system based on the number of points achieved. Most use a hierarchical decision model.
- The vast majority use prioritisation and aggregated scoring.
- Most allow the use of a prioritisation method, of which the most commonly used is the panel method, but monetisation in one (MMG) and the distance to target method could also be used in some cases.
- In all cases, the process of carrying out a multi-criteria evaluation involves the breakdown into subproblem evaluations, which can be analysed independently of each other.
- The majority of the methods apply numerical weightings to subproblem scores to establish a weighted hierarchy. About half of the methods include a kind of paired comparison between alternatives.
- Some of the methods are potentially applicable to generic process assessment.

The insights gathered in Task 2 are particularly important when it comes to designing a framework for points-systems that compares the various environmental impact criteria, but the results of the consultations with stakeholders in Task 1 showed that this approach is not supported by the majority of the Ecodesign stakeholders. Rather, it seems as if any appropriate points-based methodology needs to be re-developed in a way that is derived from experience with these other multi-criteria evaluation methods. This results in the methodological approach, which is discussed and explained in Task 3.

TASK 3 – METHODOLOGICAL FRAMEWORK FOR AN ECODESIGN POINTS-SYSTEM

Within this task a generic methodological framework for the assessment and establishment of an Ecodesign points-system that could be applied to complex products is developed. It consists of 10 steps. In the first four assessment steps, data elements are collected and organised which is necessary for determining whether a points-system approach is justified and feasible in principle. This determination is assessed in step 5 so that adequacy and feasibility can be established. Steps 6 to 9 are performed when a points-system approach is considered appropriate and must be derived as such. Step 10 examines additional measures to support the regulatory process (see Waide 2017b).

Step 1. Assessment of key lifecycle stages

This step involves evaluating the different phases of the product lifecycle from a cradle-to-grave perspective to determine which of these are relevant for potential Ecodesign measures.

Step 2. Assessment of product scope boundaries and associated impacts at the wider (extended product or product-system) level

Under this step the following assessments are performed:

- Does the product only have an impact at the level of simple products?
- Does the product have an impact on an extended product level?
- Does product design affect the broader level of the product system?

The answers to the above questions are used to identify the scope of the potential points-system. The more negative answers there are, the more likely it is that a complex product is being addressed and therefore that a points-system based approach could be useful.

Step 3. Selection of environmental impact criteria

The treatment of environmental impact criteria discussed in this section refers to the information derived from the MEErP. The MEErP has been deliberately designed to assess the environmental impact of energy-related products and thus to focus on the assessment of energy performance. It is therefore possible that in the future it may be necessary to expand its capacity to take better account of other environmental impacts such as material efficiency. Nevertheless, the methodology set out makes use of the MEErP as it currently is.

Step 4. Determination of the phases at which product design may influence lifecycle impacts

This step involves assessing the different stages of the product lifecycle from the perspective of when it is possible to consider setting requirements that would affect the eco-design performance of the product.

Step 5. Assessment of whether a points system approach is potentially merited or not

If the answer to one of the following questions is yes, a point system approach may be appropriate, otherwise it is rather unlikely.

Is there some doubt as to the practicability and quality of the eco-design performance assessment of the product because: (a) There is a mixture of quantifiable (cardinal) and more qualitative eco-design characteristics of the product, but it is appropriate to attach some value to the qualitative characteristics, as they are expected to bring environmental benefits? (b) Although it is known that the existence of specific eco-design characteristics bring environmental benefits, the relative importance of the benefit to a particular environmental impact parameter is difficult to determine reliably at the level at which the scope of a prospective regulation is likely to apply? (c) It is too complicated to apply a rigorous methodology for performance assessment in practice, but a points-based approach (allocating points depending on the eco-design characteristics used) could be an acceptable compromise that would allow requirements to be established to promote progress in a positive direction without being excessively restrictive?

Step 6. Assessment of the implications of product modularity

If a product has a modular structure (i.e. consists of modules) and each module fulfils a function that can be clearly related to a parameter of environmental impact, the contribution may be assessed. If this is the case, points could basically be awarded on a module basis and aggregated upwards in order to achieve a total score.

Step 7. Assessment of the implications of product performance sensitivity to the final application

The principal purpose of this step is to aim to identify the level(s) of stability at which a representative duty profile can be defined for the product in question.

Step 8. Determination of environmental impact budgets

The determination of the budget for the environmental impact requires the derivation of a representative duty profile for the product. This profile shall evaluate the product delivery profiles taking into account the product limit range specified in step 2. It must also be differentiated for each relevant application group, as defined in step 7. As soon as the duty profile is known, the environmental impact performance for each aspect of the duty profile can be assessed. This can be done both for the reference product and successively for product designs using design options that reduce the environmental impact in one or more phases of the duty profile. The assessment of each of these product cases includes the derivation of an environmental impact budget, broken down by phase of the duty profiles. For example, consider the energy consumption for a product with 4 operating phases (off, standby, partial load and full capacity).

Step 9. Normalisation and awarding of points

After the budgets for the environmental impact assessment have been determined in step 8 depending on the design options, the next step is to normalise the values as a preliminary stage for awarding a point scale.

Step 10. Support to regulatory decision-making

Once a points-structure has been allocated for each of the (up to two) environmental impact criteria being considered then this information can be used to assess the distribution of products available on the market (and potentially available) against the points allocation for each impact parameter in turn. In combination with an economic analysis from MEErP Task 5 and a design option analysis from MEErP Task 6, it would be possible to develop policy impact scenarios for the market for new products that move towards specific point distributions in response to Ecodesign implementation measures and energy labelling.

TASK 4 – CASE STUDIES

Under this task the two product groups of data storage and machine tools are evaluated by using the method proposed in Task 3. In this paper the machine tools case is presented in the next section.

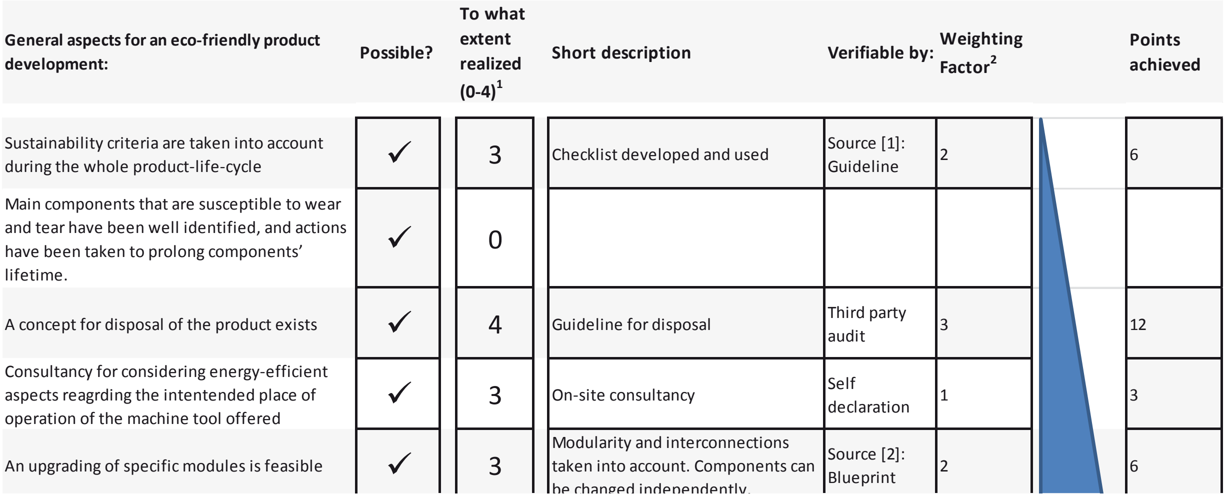
A case study of the generic points methodology applied to Machine Tools

After defining a generic Ecodesign point system for complex products in Task 3, the case study applies this methodology to machine tools. The methodology follows the same steps described in the Task 3 report, but is applied to the specific application of machine tools. The reader should note that the example given here is applied to a hypothetical machine tool type to test the proof of concept. This paper highlights how the method addresses the problem of a missing reference system/product, and focuses the case study on steps 8 (Determination of environmental impact budgets) and 9 (Normalisation and awarding of points). By means of step 4 (Determination of the phases at which product design may influence lifecycle impacts) three lifecycle stages were identified as especially important: the stage of product development; the detailed design stage; and the use phase. The early stage of product development has a high impact on the final energy use. But the potential to concretely assess environmental impacts via measurement, calculation or simulation in those early stages is rather low. In the detailed design phase, the product designer has a very direct influence on the product's environmental impacts, as the designer is selecting and designing the individual components of the product. The potential to assess those impacts is very high. And finally, the way the product is used also has a very significant impact on its energy consumption and thus measures that influence the user behavior are important and need to be taken into consideration. Nonetheless, the potential for the designer to influence user behavior is limited and subject to high uncertainty. In the following text the procedure applied during these three stages as well as the final assembly of the points into a final score will be described in detail (see Hettesheimer et al. 2017).

DETERMINATION OF ENVIRONMENTAL IMPACT BUDGETS IN THE PRODUCT DEVELOPMENT STAGE

The aim during the product development phase is to encourage machine tool designers to introduce a design process that takes into account the environmental impact of their designs and systematically considers the means to reduce them. Using a checklist methodology to be followed during the design process is probably the most straightforward way to promote this. The precise definition of the criteria to be included in the list should be specified in a more detailed analysis of all potential elements of the checklist and their potential application. The extent that there is credible evidence that the checklist methodology has been followed during the design process could also be included in the scoring of points for this phase, so that greater documentation could be given a higher weighting. An example extract of how such a checklist might be structured is depicted in Figure 2.

The first column of the checklist might serve to register if the listed aspect can be taken into consideration or can be implemented. If it is the case, this will be considered with regard to the maximum achievable score. The second column demands whether it has been realized, and to what extent. The values assigned to the scale are used as weightings for the overall score achievable by these aspects. The scale might range from 0 (aspect not realised) to 4 (extremely well re-



General aspects for an eco-friendly product development:	Possible?	To what extent realized (0-4)^1	Short description	Verifiable by:	Weighting Factor^2	Points achieved
Sustainability criteria are taken into account during the whole product-life-cycle	✓	3	Checklist developed and used	Source [1]: Guideline	2	6
Main components that are susceptible to wear and tear have been well identified, and actions have been taken to prolong components' lifetime.	✓	0				
A concept for disposal of the product exists	✓	4	Guideline for disposal	Third party audit	3	12
Consultancy for considering energy-efficient aspects reagrding the intentended place of operation of the machine tool offered	✓	3	On-site consultancy	Self declaration	1	3
An upgrading of specific modules is feasible	✓	3	Modularity and interconnections taken into account. Components can be changed independently.	Source [2]: Blueprint	2	6

Figure 2. Extract of an example checklist.

alised). In column four, the action should be verifiable via the additional information. To pay attention to the different degrees of documentation evidence, a weighting hierarchy is provided wherein: self-declaration could be rewarded with a weighting score of one; evidence-based documentation could be taken into account by a weighting of two; and an external evaluation via a third party audit could be weighted with a score of three. So, if all necessary information is provided and the aspect was realised to a high extent, a maximum of 12 points can be achieved (4 points for the degree of realization, multiplied by 3 points for the fullest and most reliable documentation). If additional information to support verification is not given, or the short description is missing, no points could be given at all. Where an aspect is impossible to be implement, or to be considered, an explanation has to be given as to why. If the argument put forward is valid, this aspect is not considered when calculating the maximum achievable score. By doing so an overall score for the development stage can be calculated.

DETERMINATION OF ENVIRONMENTAL IMPACT BUDGETS IN DETAILED PRODUCT DESIGN STAGE

The assessment of the environmental impacts of the components is carried out using a cardinal scale and through assigning deemed energy savings for the different design options which can be applied to a specific module of a machine tool.

The assessment within this step is comprised of several substeps:

1. Definition and population of the design option in a correlation matrix
2. Identification of the relevant operating states
3. Identification of generic energy saving potentials
4. Identification of the case for assessment
5. Identification of the reference case
6. Identification of the BAT (Best Available Technology) case
7. Determination of the relative performance of the selected design

Detailed product design stage – definition of the correlation matrix

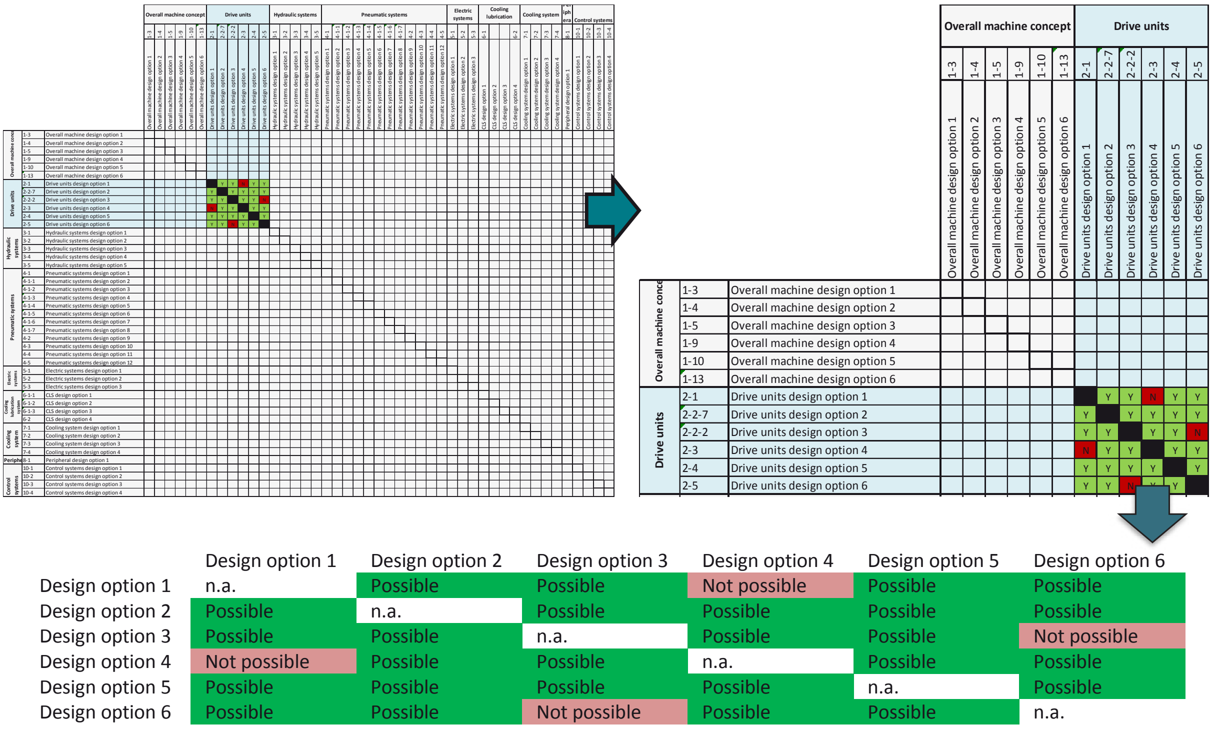
The ISO 14955-1:2014 standard gives examples for potential energy saving options for each module; however, implementation of these saving options could be mutually exclusive. Therefore, a correlation matrix for all potential saving options needs to be created to determine which options cannot be deployed simultaneously. Applying matrix gives a pairwise comparison of all design options. The objective of this comparison is the elimination of options which are not feasible or offer no benefit as well as detection of those features which are mutually exclusive. In the latter case, the option offering the higher saving potential should be preferentially considered. The compatibility of different combinations of design options in the case of a module "Drive unit" is shown in the matrix below. For each combination of the different design options the matrix indicates, whether they can be combined in the product or not. A case where such a combination of design options would not be possible or at least would make no sense would be the case when a drive unit with a "Regenerative feedback of inverter system (servo motor/ spindle)" would be implemented and at the same time the overall machine concept would be equipped with "Axis clamping".

Detailed product design stage – identification of the relevant operating states

For each module, the relevant operating states need to be identified. The operating states can be chosen in accordance with ISO 14955-1:2014, Annex D, but are not limited to this standard. For the case study four operating states are used for illustrative purposes: off; standby with peripheral units off; warm-up; and processing.

Detailed product design stage – identification of generic energy saving potentials

After defining the relevant operating states, generic energy savings need to be defined for each energy efficiency design option and for each operating state (preferably in accordance with ISO 14955-1). The energy savings should be representative of the realistic saving potential, which results in an energy saving matrix for each module. Table 2 shows an example for a hypothetical drive unit.



	Design option 1	Design option 2	Design option 3	Design option 4	Design option 5	Design option 6
Design option 1	n.a.	Possible	Possible	Not possible	Possible	Possible
Design option 2	Possible	n.a.	Possible	Possible	Possible	Possible
Design option 3	Possible	Possible	n.a.	Possible	Possible	Not possible
Design option 4	Not possible	Possible	Possible	n.a.	Possible	Possible
Design option 5	Possible	Possible	Possible	Possible	n.a.	Possible
Design option 6	Possible	Possible	Not possible	Possible	Possible	n.a.

Figure 3. Exemplary correlation matrix for a module "drive unit" and resulting combinations of design options.

Table 2. Energy saving potentials for design options compared to the reference case.

Operating state	Off	Standby with peripheral units off	Warm Up	Processing
Reference case	0.0	0.0 %	0.0 %	0.0 %
Design option 1	0.0	1 %	2 %	1 %
Design option 2	0.0	3 %	-2 %	2 %
Design option 3	0.0	1 %	2.5 %	2.5 %
Design option 4	0.0	2 %	3 %	1 %
Design option 5	0.0	3 %	2 %	3 %
Design option 6	0.0	1.5 %	1.75 %	4 %

Each savings figure is defined for the individual design option savings compared to the reference model. It is assumed that the savings expected from a combination of the design options can be calculated by a multiplicative combination of the individual savings. The correlation matrix shows which of these combinations can be realised in the product. It may also be that a saving option leads to an increase in energy use in one operating state, as for Design option 2 during the Warm Up phase.

Detailed product design stage – identification of the case for assessment

For the design options which are actually selected for the machine tool in question, the power intake and annual energy consumption have to be determined for each of the identified operating states. Those values could either be determined by measurement or derived from the design calculations. The fractions of time spent in each mode are derived from the operating hours of the product.

The machine tool presented is off during most weekends leading to ~2,200 Off mode hours per year. During workdays, the machine tool is operative for ~6.5 hrs. per day, in warm up for another ~3 hrs. and in standby for ~14.5 hrs., which gives the breakdown shown in Table 3.

Detailed product design stage – identification of the reference case

For many Ecodesign assessments where an energy efficiency index is determined, the reference case is a product that is representative of the average energy performance on the market at a given time. However, this is much less suitable for highly heterogeneous products, whose performance is sensitive to the duty profile and the task being set. For machine tools, there are simply too many variables to have confidence in defining a generic energy efficiency index. Rather, it makes sense to use the approach set out in ISO 14955-1:2014 that lists energy saving design options and to compare these to the options deployed in a product specific base case. A first tendency for the typical savings expected from their use can

Table 3. Annual Breakdown of Energy use of the selected design (for a hypothetical drive unit).

Actual design-Energy use	Off	Standby with peripheral units off	Warm-Up	Processing	Total
Fraction of time	25 % (~2,200 hrs.)	45 % (~3,950 hrs.)	10 % (~850 hrs.)	20 % (~1,750 hrs.)	100 %
Power Intake (kW)	0.00	0.10	1.20	1.94	0.55
Energy use (MWh/year)	**0.0**	**0.8**	**10.5**	**17.0**	**4.8**

Table 4. Comparative energy demand: Selected design options compared to the reference case.

	Off	Standby with peripheral units off	Warm Up	Processing
Reference case	0.0	0.0	0.0	0.0
Design option 1	0.0	1 %	2 %	1 %
Design option 2	0.0	3 %	-2 %	2 %
Design option 3	0.0	1 %	2.5 %	2.5 %
Design option 4	0.0	2 %	3 %	1 %
Design option 5	0.0	3 %	2 %	3 %
Design option 6	0.0	1.5 %	1.75 %	4 %

Actual design Relative energy use	Off	Standby with peripheral units off	Warm-Up	Processing
Design option 1	100%	99%	98%	99%
Design option 2	100%	97%	102%	98%
Actual Design	100%	96%	100%	97%

be derived from the ENTR Lot 5 Preparatory Study (Schischke et al. 2012).

Thus, a reference case may be defined to be a product which has none of these energy-saving options. If the reference case is considered to be the same product but with no energy saving design options, then it represents the solution with the lowest energy efficiency for the given task, and hence defines the lower performance boundary. By contrast, the best available technology (BAT) is the product which incorporates all the available and mutually compatible high efficiency design options, and hence defines the other end of the spectrum from the reference case.

Tables 4–7 show an example of this type of calculation for a hypothetical machine tool drive unit module, in which two design options are incorporated into the actual design. As a result of both design options being implemented, the "actual design" compared to the reference case is calculated via the resulting percentage from multiplying the design option 1 percentage by the design option 2 percentage. In the case of the standby mode the Relative energy use of Design option 1 is: 100 % - 1 % = 99 % and for Design option 2: 100 % - 3 % = 97 %. By multiplying both values, this results in a relative energy use of the selected design compared to the reference case of 96 % (99 % × 97 % = 96 %).

Then by dividing the energy use of the selected design (determinable by measurement or design calculations, see "Detailed product design stage – identification of the case for assessment" above) by the relative energy use values, allows calculate the energy use of the reference case (e.g. in the standby mode: 0,8 MWh/year: 0,96 = 0,83 MWh/year). The absolute energy savings of the actual design are calculated as the difference in energy consumption to the reference case.

Detailed product design stage – identification of the BAT case

A specific case has to be defined for each potential combination of design options as identified during the definition of the correlation matrix (see "Detailed product design stage – definition of the correlation matrix" above). For each case, the overall savings are then determined by considering the duty profile and savings potentials under each phase. Two general cases have to be considered in building the BAT cases:

- All design options decrease the energy demand for all stages of the duty profile
- One or more design options increase(s) the energy demand in at least the "on" stage of the duty profile.

For both alternatives, the cases are built from the matrix of all potential combinations of measures, compared to the possible combinations. For example, a combination of design options 1, 2, 4 and 5 is not possible, as the options 1 and 4 are incompatible. The same is true for options 3 and 6 (see Figure 3).

For each case (which might be the BAT case for our machine tool), the cumulative savings can be calculated by the multiplicative combination of the individual options. Thereby the reference case always has 100 % energy use. For example, case 5 includes design options 1, 3 and 5. In the standby mode this results in savings of 1 %, 1 % and 3 % (see Table 4). The energy demand of case 5 in standby mode compared to the reference case is therefore calculated as the product of the three design options: (100 % - 1 %) × (100 % - 1 %) × (100 % - 3 %) = 95 %.

The maximum savings depend on the duty profile. In standby mode, Case 3 shows the highest savings, while Case 7 does in warm up and Case 4 does in full (processing) load (see Table 6 upper table on the left). In total, Case 4 has the lowest total energy consumption and is therefore selected as the BAT case (see Table 6 – lower table).

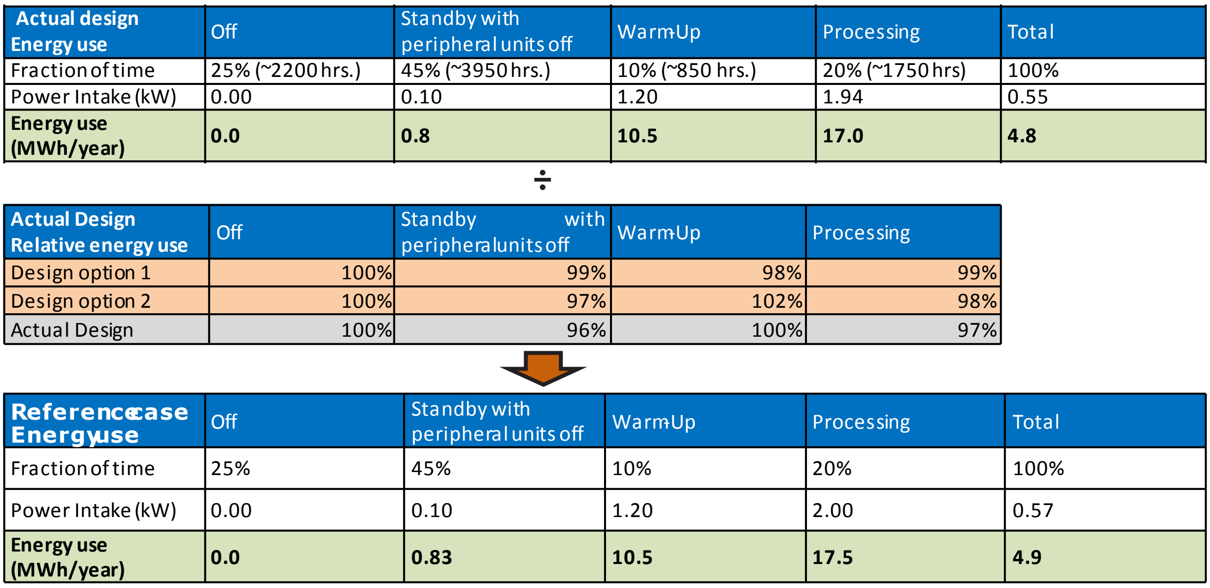
Based on the analyses it is now possible to define the energy use in each phase of the duty profile of the reference case, the BAT case and the selected design, as shown in Table 7 for the hypothetical drive unit. Further modules can be taken into account in the same manner.

To sum up, by following the steps described in this section it is possible to define a reference case and also a BAT case in accordance to a specific application profile of a intended machine tool, even if no other comparable reference product is available.

DETERMINATION OF ENVIRONMENTAL IMPACT BUDGETS IN THE USE PHASE

As user behaviour has a significant impact on energy consumed in the use phase and in theory it is possible to improve machine tool operator actions by providing good guidance. This phase is intended to recognise the impact that such guidance can have on the product's final energy consumption. However, criteria are qualitative and are of a very similar nature to those considered in the product development stage, and hence a checklist seems to be a fitting method to assess these criteria. Accordingly, the means of completing the form happens in the same way and will therefore not be further described at this point.

Table 5. Energy use of the reference case hypothetical drive unit.



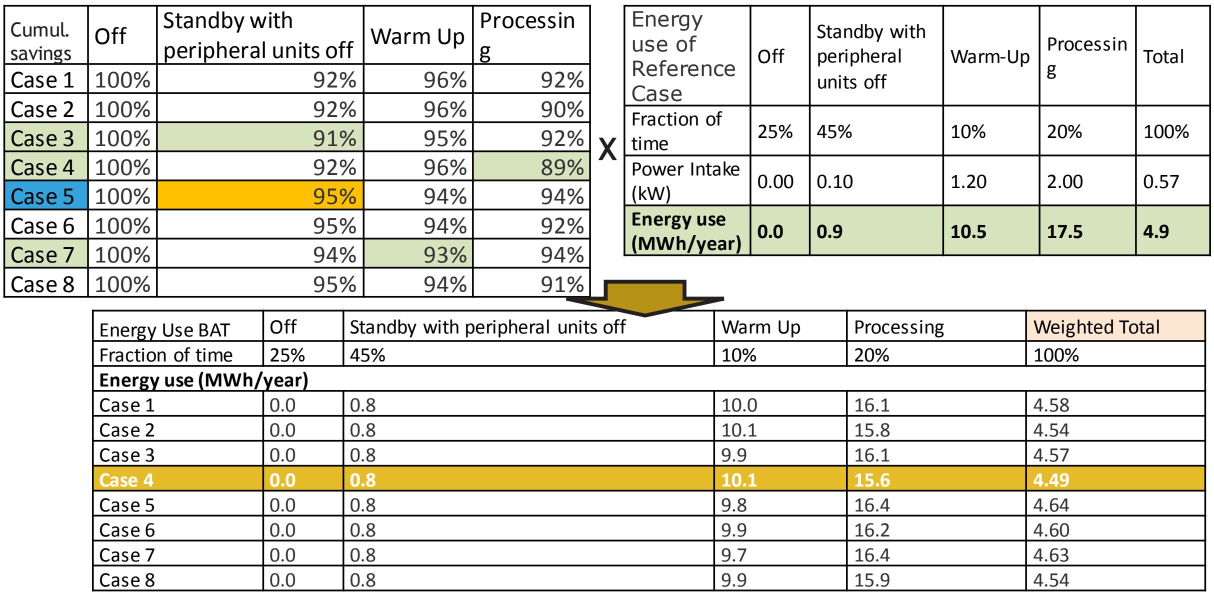
Actual design Energy use	Off	Standby with peripheral units off	Warm-Up	Processing	Total
Fraction of time	25% (~2200 hrs.)	45% (~3950 hrs.)	10% (~850 hrs.)	20% (~1750 hrs)	100%
Power Intake (kW)	0.00	0.10	1.20	1.94	0.55
Energy use (MWh/year)	**0.0**	**0.8**	**10.5**	**17.0**	**4.8**

÷

Actual Design Relative energy use	Off	Standby with peripheral units off	Warm-Up	Processing
Design option 1	100%	99%	98%	99%
Design option 2	100%	97%	102%	98%
Actual Design	100%	96%	100%	97%

Reference case Energy use	Off	Standby with peripheral units off	Warm-Up	Processing	Total
Fraction of time	25%	45%	10%	20%	100%
Power Intake (kW)	0.00	0.10	1.20	2.00	0.57
Energy use (MWh/year)	**0.0**	**0.83**	**10.5**	**17.5**	**4.9**

Table 6. Potential energy use of the hypothetical drive unit cases.



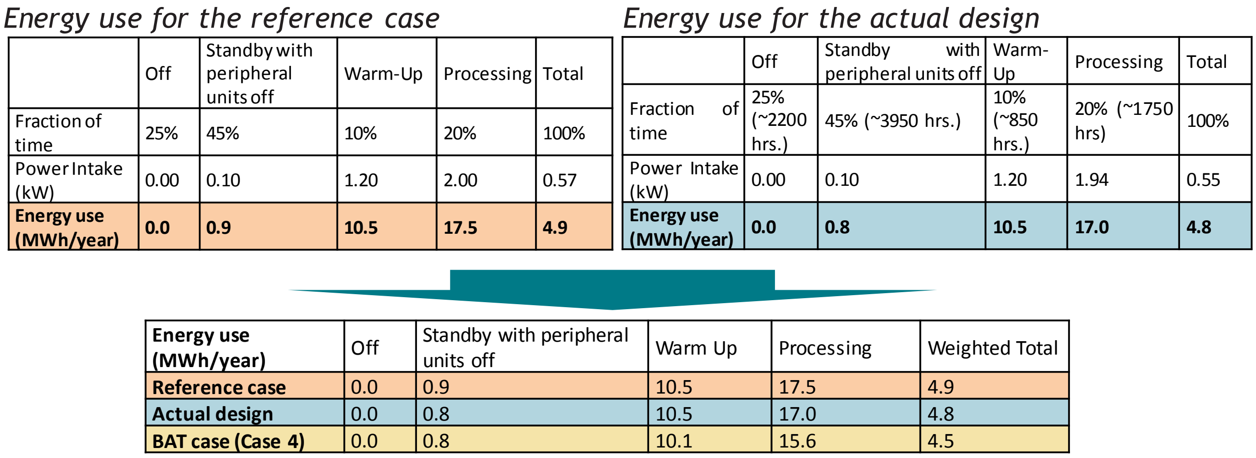
Cumul. savings	Off	Standby with peripheral units off	Warm Up	Processing
Case 1	100%	92%	96%	92%
Case 2	100%	92%	96%	90%
Case 3	100%	91%	95%	92%
Case 4	100%	92%	96%	89%
Case 5	100%	95%	94%	94%
Case 6	100%	95%	94%	92%
Case 7	100%	94%	93%	94%
Case 8	100%	95%	94%	91%

X

Energy use of Reference Case	Off	Standby with peripheral units off	Warm-Up	Processing	Total
Fraction of time	25%	45%	10%	20%	100%
Power Intake (kW)	0.00	0.10	1.20	2.00	0.57
Energy use (MWh/year)	**0.0**	**0.9**	**10.5**	**17.5**	**4.9**

Energy Use BAT	Off	Standby with peripheral units off	Warm Up	Processing	Weighted Total
Fraction of time	25%	45%	10%	20%	100%
Energy use (MWh/year)					
Case 1	0.0	0.8	10.0	16.1	4.58
Case 2	0.0	0.8	10.1	15.8	4.54
Case 3	0.0	0.8	9.9	16.1	4.57
Case 4	**0.0**	**0.8**	**10.1**	**15.6**	**4.49**
Case 5	0.0	0.8	9.8	16.4	4.64
Case 6	0.0	0.8	9.9	16.2	4.60
Case 7	0.0	0.8	9.7	16.4	4.63
Case 8	0.0	0.8	9.9	15.9	4.54

Table 7. Energy use of the reference case, selected design and BAT – example of a hypothetical drive unit.



Energy use for the reference case

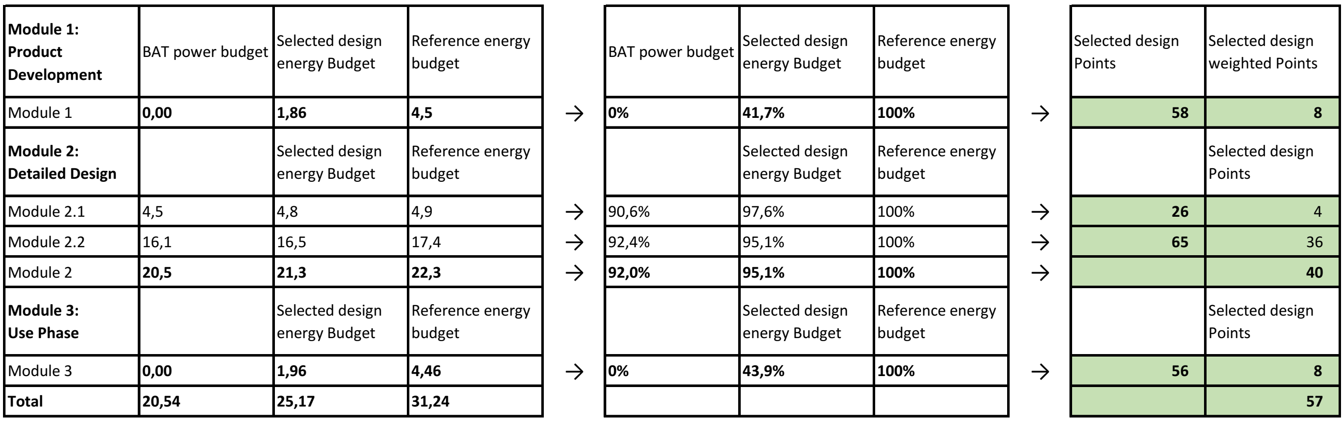
	Off	Standby with peripheral units off	Warm-Up	Processing	Total
Fraction of time	25%	45%	10%	20%	100%
Power Intake (kW)	0.00	0.10	1.20	2.00	0.57
Energy use (MWh/year)	**0.0**	**0.9**	**10.5**	**17.5**	**4.9**

Energy use for the actual design

	Off	Standby with peripheral units off	Warm-Up	Processing	Total
Fraction of time	25% (~2200 hrs.)	45% (~3950 hrs.)	10% (~850 hrs.)	20% (~1750 hrs)	100%
Power Intake (kW)	0.00	0.10	1.20	1.94	0.55
Energy use (MWh/year)	**0.0**	**0.8**	**10.5**	**17.0**	**4.8**

Energy use (MWh/year)	Off	Standby with peripheral units off	Warm Up	Processing	Weighted Total
Reference case	0.0	0.9	10.5	17.5	4.9
Actual design	0.0	0.8	10.5	17.0	4.8
BAT case (Case 4)	0.0	0.8	10.1	15.6	4.5

Table 8. Exemplary application of the normalization step.



Module 1: Product Development	BAT power budget	Selected design energy Budget	Reference energy budget		BAT power budget	Selected design energy Budget	Reference energy budget		Selected design Points	Selected design weighted Points
Module 1	**0,00**	**1,86**	**4,5**	→	**0%**	**41,7%**	**100%**	→	**58**	**8**
Module 2: Detailed Design		Selected design energy Budget	Reference energy budget			Selected design energy Budget	Reference energy budget			Selected design Points
Module 2.1	4,5	4,8	4,9	→	90,6%	97,6%	100%	→	**26**	4
Module 2.2	16,1	16,5	17,4	→	92,4%	95,1%	100%	→	**65**	36
Module 2	**20,5**	**21,3**	**22,3**	→	**92,0%**	**95,1%**	**100%**	→		**40**
Module 3: Use Phase		Selected design energy Budget	Reference energy budget			Selected design energy Budget	Reference energy budget			Selected design Points
Module 3	**0,00**	**1,96**	**4,46**	→	**0%**	**43,9%**	**100%**	→	**56**	**8**
Total	**20,54**	**25,17**	**31,24**							**57**

ASSEMBLING THE ENERGY BUDGET

To be consistent with the Task 3 methodology each of the three stages needs to be allocated a share of the overall energy budget in proportion to their expected impact on the overall energy performance of the product. The Task 3 methodology suggests that each stage is allocated a share of the total energy consumption of the machine tool in relation to its influence on the total energy consumption. For stages 1 (product development) and 3 (use), this is not measurable in the normal sense, so that a process would have to be agreed upon in order to decide how much of the total energy budget is spent for stages associated with product development and use, whereby it is determined that these stages in reality do not consume any energy, but help to save it. Therefore, these stages would have to receive a part of the total energy budget of the detailed design stage which reflects their expected contribution to the energy performance of the machine tool. The actual energy balance is then calculated from the relative performance of the previously calculated product. However, for some Stage 1 and Stage 3 features, it may largely be a matter of engineering judgement. As such, these would seem to be areas where a panel approach or, for example consulting experts via a pairwise Analytical Hierarchy Process (AHP) would be appropriate, to help to reach a weighted decision.

NORMALISATION AND AWARDING OF POINTS

As a last step, the methodology of Task 3 suggests that the values given in the energy budget are normalised by comparison with a reference product. From this, a performance indicator is derived that can be converted into a total score.

Table 8 shows an exemplary application of the normalization step. The energy budgets of the selected design are related to the reference energy budget (The exemplary determination of the energy budget of module 2.1 was thereby explained in the former tables). The total score is calculated as a weighted average of the individual power budgets.

The simplest way to award points is to set the reference product to 0 points and the BAT product to 100 points. The actual design would be awarded to points relative to this scale. The points for each module are weighted according to the reference energy budget and finally summed up. The selected design in the example above would be awarded 57 points. A regulation could be implemented by setting a minimum threshold for the overall product as well as individual thresholds for each module.

Discussion, Conclusion and Outlook

Ecodesign has been the most successful policy tool targeting product efficiency in the EU. Still, the classic approach using energy performance indicators related to a functional unit has its limit regarding complex products. Machine tools have been one of the most discussed product groups within the Ecodesign process due to their complexity. Within this paper, we have presented an approach to tackle the specific challenges of a complex product based on a points-system methodology developed for the European Commission.

With this approach, it is possible to cover the broad variety of impact parameters within a consistent assessment methodological framework. Other than in the "classical" Ecodesign approach using minimum energy performance limits the methodology allows for the assessment of a broad spectrum of parameters. This variety is achieved at the cost of detailed assessment in individual parameters to keep the system flexible and usable. Therefore, besides cardinal parameters, ordinal parameters are used, which rely more on an engineering assessment than on empirical evidence. Other than empirically determined parameters, they come along with a certain subjectivity even when using methods like AHP. As the methodology relies on a broad range of parameters and requires an in-depth knowledge of the individual product, the assessment is not as easy to follow as an assessment relying on one or just a few energy performance indicators. Still, all steps and assessments are transparently documented and can be subject to an external review. Comparable systems are commonly used for the certification of buildings (e.g. BREAM, LEED & DGNB) even in regulatory contexts. Also in other regulatory processes, such engineering assessments are part of the process.

The presented case study is intended as a proof of concept rather than a full-scale implementation of the methodology as no specific real-life machine tool has been used for the assessment, but rather a hypothetical example. The application to an existing product would require in-depth knowledge of the specific machine tool, which was not available in the context of the study. Before applying the methodology in a broader regulatory context, a full-scale application would be appropriate.

References

European Commission (2014) Working Document for the Ecodesign Consultation Forum on Machine Tools and Related Machinery. Brussels (2014).

Hettesheimer, Tim; Rohde, Clemens; Waide, Paul (2017): Technical assistance study for the assessment of the feasibility of using "points system" methods in the implementation of Ecodesign Directive (2009/125/EC). TASK 4 – Machine Tools Case Study. Brussels.

ISO (2014) 14955-1:2014 Environmental evaluation of machine tools – Part 1: Energy-saving design methodology for machine tools. International Organization for standardization, Geneva, Switzerland.

Peeters, Karolien; Rohde, Clemens; Waide, Paul; (2017): Technical assistance study for the assessment of the feasibility of using "points system" methods in the implementation of Ecodesign Directive (2009/125/EC). TASK 2 – A review of state-of-the art methods. Brussels.

Schischke, K., Hohwieler, E., Feitscher, R., König, J., Nissen, N. F., Wilpert, P., & Kreuschner, S. (2012) Energy-Using Product Group Analysis – Lot 5 Machine tools and related machinery – Task 5 Report – Technical Analysis BAT and BNAT.

Waide, Paul (2017a): Technical assistance study for the assessment of the feasibility of using "points system" methods in the implementation of Ecodesign Directive (2009/125/EC). TASK 1 – Stakeholder consultation. Brussels.

Waide, Paul (2017b): Technical assistance study for the assessment of the feasibility of using "points system" methods in the implementation of Ecodesign Directive (2009/125/EC). TASK 3 – Method development. Brussels.

Acknowledgements

We gratefully acknowledge the support of the European Commission, DG Grow framework contract No 409/PP/2014/FC Lot 2 (January 2016 to July 2017). The responsibility of this publication lies with the authors. They would like to express their gratitude to all participants involved in the process and stakeholder meetings.