Chapter 20
Technical and Economic Benchmarking Guideline for the Compensation and Correction of Thermally Induced Machine Tool Errors

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Abstract The approaches to the correction and/or compensation of thermally caused machining errors developed in the CRC/TR 96 have different effects on the accuracy that can be achieved and on the throughput capacity. Consequently, the approaches generate different benefits. At the same time, the costs and time required for their generation and application differ as well. As a result, not only the technical, but also the economic consequences of each method in terms of its usability for practice-relevant applications are of interest to potential users. Methods for comparing the various approaches are developed in subproject C05. These methods are based on the technical and economic benchmarking guidelines introduced in the paper.

20.1 Introduction

The goal of the research activities is a holistic, comparative assessment or benchmarking of the compensation and correction methods (Fig. 20.1) developed. The term holistic here includes specifying the consequences for the machine tool development process resulting from the solutions, as well as comparing the solutions' suitability for different conditions of use in a high-quality and cost-effective operation. The requirements to be fulfilled by a holistic benchmarking method like this are as follows:

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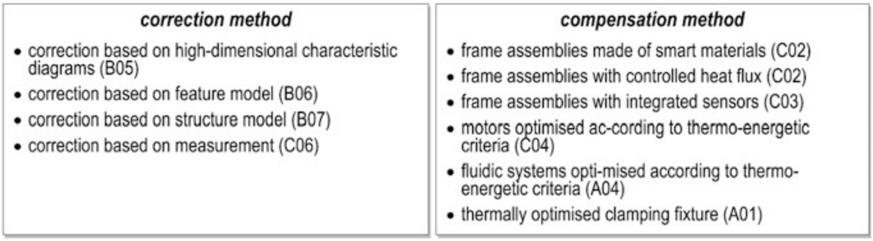
K. Großmann (ed.), *Thermo-energetic Design of Machine Tools*,
Lecture Notes in Production Engineering, DOI 10.1007/978-3-319-12625-8_20



correction method

- correction based on high-dimensional characteristic diagrams (B05)
- correction based on feature model (B06)
- correction based on structure model (B07)
- correction based on measurement (C06)

compensation method

- frame assemblies made of smart materials (C02)
- frame assemblies with controlled heat flux (C02)
- frame assemblies with integrated sensors (C03)
- motors optimised ac-cording to thermo-energetic criteria (C04)
- fluidic systems opti-mised according to thermo-energetic criteria (A04)
- thermally optimised clamping fixture (A01)

Fig. 20.1 Correction and compensation methods, assigned to the subprojects

- The compensation and correction methods, whose application results in different machine configurations, have to be described by their distinguishing features and the parameters relevant for benchmarking.
- The various technological use cases have to be formulated. The operational performance- and market-related constraints have to be involved.
- For benchmarking of methods, evaluation criteria for benefit and cost (such as additional resources needed) have to be formulated.

There is at present a lack of benchmarking methods that combine technical and economic aspects. As a rule, the technical efficacy of innovative solutions is assessed based on experience. The technical benchmarking of machine tools has hitherto been conducted with regard to individual aspects. Abele et al. (2010), Lindner and Götze (2011) and Denkena et al. (2010) proclaim that life cycle costs are suitable for a cost-related balancing of machine tools. The VDMA standard sheet no. 34160 predefines the conditions for their determination (Verband Deutscher Maschinen- und Anlagenbau e.V. 2012). Lindner and Götze (2011) propose to model the components as well as the development and operational processes of the machine tools as a basis for cost determination, for which basic features are lacking. Domain-specific languages adapted for business process modelling, as mentioned in Zor et al. (2011), could provide support.

Strategic models that make it possible to evaluate technological feasibility and profitability at an early point in the development process were developed, among others in Ehrlenspiel (2009) and Eversheim and Schuh (2005). These models were created at the level of development and design methods and of engineering management. However, no immediate relationships to the business analysis of the workflows exist that are connected with the development.

The determination of the machine tool's accuracy is an essential issue for benefit benchmarking from the CRC/TR 96's perspective. There exist sufficiently established largely standardised measurement techniques, such as (DIN 1999), on the one hand. On the other hand, test parts are frequently used, which—however—are not particularly designed to detect thermally induced errors.

Consequently, powerful individual methods are available, but, as a rule, they require detailed data that are not available to the CRC/TR 96. This is mainly information about the machine tool development costs and company-specific organisational sequences connected with the machine tool. These stand-alone approaches are not purposefully integrated into a technical-economic benchmarking method. This means that the methods available do not work in practice.

As a result, the current research is aimed at a suitable benchmarking model mapping the characteristics of the correction and compensation methods and their potential cases of application, as well as the interactions with the business environment, which comprises cost-benefit evaluation criteria for the comparison of the methods. Techniques are also needed that can determine the required information or parameters as efficiently as possible. The model is expected to provide benchmarks first for the methods to be developed within the scope of the CRC/TR 96 in order to define real states and elucidate improvement potential. Finally, the model should also be made available to the machine tool manufacturers and users to provide decision support when implementing the techniques in a machine tool or purchasing a machine tool.

20.2 The Benchmarking Model

The general model developed for benchmarking is shown in Fig. 20.2. The model brings together the required technical and economic levels of consideration and consists of the following partial models: “machine tool configuration”, into which the compensation and correction methods are integrated, “technological application cases”, “operational constraints” and “market-related constraints”. The benchmarking model also includes the “metrics for the valuation criteria” to assess benefit, cost and time, as well as the methods for determination of parameters and benchmarking.

Figure 20.3 introduces the guidelines for the economic comparison of the methods. For benchmarking purposes, the compensation and correction methods

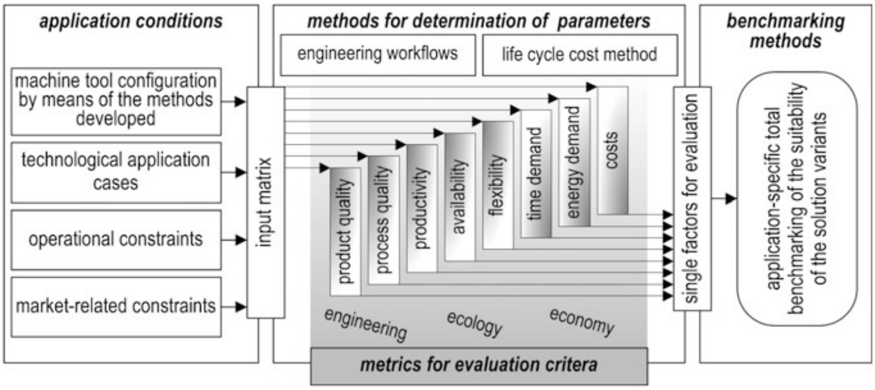


Fig. 20.2 Model approach to assess the methods intended to reduce the thermally induced machine tools’ dislocations

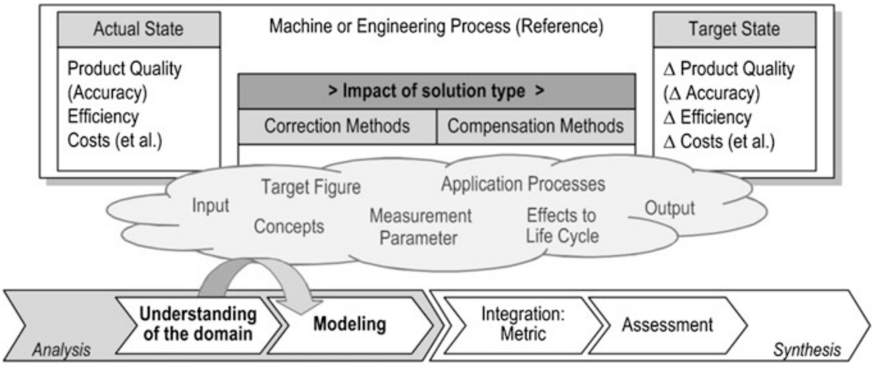


Fig. 20.3 Method assessment framework (Braun and Esswein 2014)

developed must first be brought into a system in a standardised manner, as well as the fundamental concepts to be represented by their input and output variables. It is also necessary to analyse the activities of the subprojects and to document the expected workflows that are affected by the development, implementation and application of the methods. Furthermore, the workflows' effects on the machine life cycle costs have to be estimated. Finally, all of the factors in the evaluation are brought together in a metric for holistic benchmarking. Further details on the framework are described in Braun and Esswein (2014).

The strategy of conceptual modelling (Schütte and Rotthowe 1998) which is common in business informatics, is employed for systematic analysis and representation of the workflows for the development, implementation and use of the CRC/TR 96 methods and connected with the model-based management approach (Esswein et al. 2010).

20.2.1 Partial Model "Machine Tool Configuration"

The "machine tool configuration" partial model describes the machine superstructures that result from a potential application of the different methods in a basic machine. A hierarchic functional structure is chosen for a simple and clearly structured representation of the machine tool configuration. The compensation and correction methods are integrated as a function into the basic machine structure. The benchmark-relevant factors are also entered into the partial model according to function.

The detail level of the hierarchic functional structure is modified according to each task. Thus, two levels are sufficient in order to represent different methods in a basic machine (see Fig. 20.4a). Additional details in the functional structure are needed to benchmark the methods for different basic machine tools that, for example, differ in their frame design type (Fig. 20.4b). Modelling can be supported

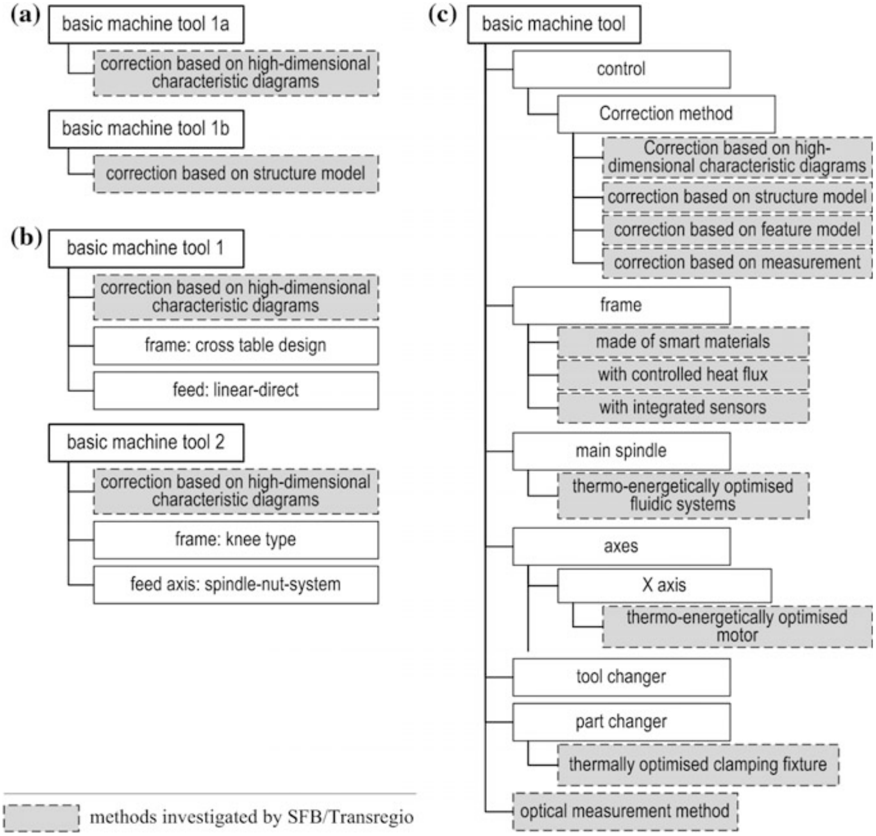


Fig. 20.4 Hierarchic functional model as a basis for the partial model "machine tool configuration" **a** method for a basic machine, **b** method for different basic machines, **c** general classification of the machine tool's functions

by specifying a general system (Fig. 20.4c) with the commonly used functional characteristics and the methods traced. The concrete machine tool configuration is defined from this system by selection of the corresponding functions.

20.2.2 Application Conditions

A machine tool configuration's suitability for the operator's purposes has to be assessed by taking into account the current application conditions. For this reason, the application conditions are shaped by the "technological application cases", "operational constraints" and "market-related constraints" together.

The “technological application cases” involve data for the parts to be machined, such as size, required tool number, lot size and accuracy requirements. It is possible to derive typical machining and setup times, as well as the process output, by using these data. From lot size, it can be determined how often the machine tool has to be reset for another workpiece (classification in Fig. 20.5 according to Schlegel 2002).

The “operational constraints” represent relevant data on production, such as the work time regime or air-conditioning of the factory floor. Run and down times, as well as the restart frequency of the machine tool, result from the work time regime, whereas air conditioning of the factory floor influences the transmission of external thermal influences to the machine tool (Wiemer et al. 2014). The “market-related constraints” consider different cost situations in purchasing, as well as for energy and personnel.

To simplify the considerations of the new methods’ benchmark, first, the same market-related constraints and the same operational constraints are assumed for all operators. Thus, the technological application conditions are the only variable. Three reference cases that are typical for the industry were chosen from the assortment of potential technological application cases (see Fig. 20.5):

- “Diemaking”: workpieces of 5,000 mm max. edge length, 1–5 pieces, high tool number
- “Mechanical engineering”: workpieces of max. 800 mm edge length, part quantity 100, medium number of tools
- “Motor manufacturing”: parts of max. 200 mm edge length, part quantity 10,000, low tool number.

The outcomes of the application condition benchmarking can also be applied by the machine tool manufacturers, since they know under what conditions the

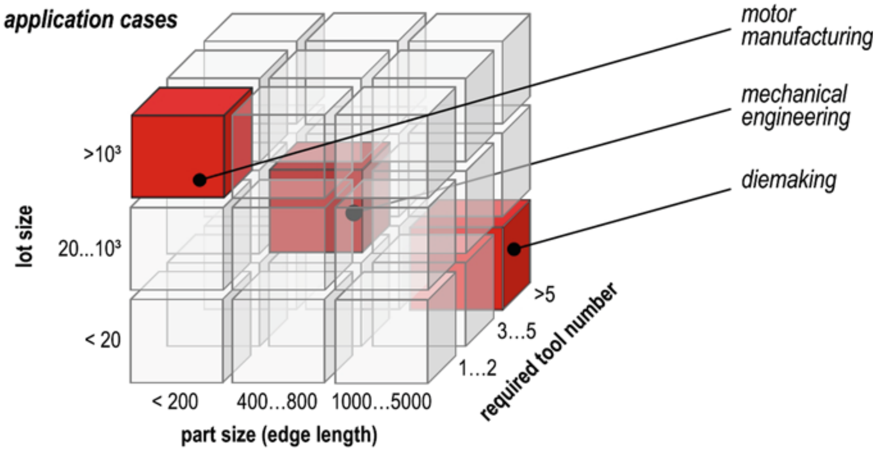


Fig. 20.5 Technological application cases for which the machine tool’s suitability has to be assessed

machine tools are really run. To assess the effect of the methods on the machine tool, the cases of special-purpose machines and series machines are differentiated. This classification makes sense in order to take into account the copy-cost effect in case of a potential multiple use of correction methods.

20.2.3 Benchmarking Criteria

For the reference application cases chosen, the suitability of the compensations and correction methods is judged according to the benchmarking metric in terms of benefit and costs. A method's benefit is benchmarked via properties to be determined, and these properties are described in the following section. When estimating the necessary time and costs, consideration is given to the additional expenses necessary during development, implementation, commissioning and operation of such a machine in comparison with those for a machine tool functioning without compensation and correction methods.

20.2.3.1 Benchmarking Criteria for Benefit Description

The benefit of a method represents the achievable improvements in the machine tool's performance in terms of increased accuracy, shorter machining times and/or lower energy consumption. To determine the parameters for benefit assessment, established methodologies are investigated to determine their usability in general and their efficient usability in particular, as well as, if possible, the potential for modifications designed to meet the specific requirements of the CRC/TR 96. Initially selected evaluation criteria that represent the benefit are detailed.

Machining Accuracy

For a machine tool, the term "machining accuracy" indicates the product quality that can be achieved in the shape and positional tolerances of the part. Different factors, such as geometry, statics and dynamics, as well as the machine's positioning performance, affect the machining accuracy (Verein Deutscher Ingenieure 1977). These factors are not influenced by thermal behaviour and have to be considered separately from the total behaviour for thermal behaviour investigations. For machine tools, this can be done by machine analyses both in the cold and warmed states. The machine is subjected to a thermal load through an appropriate introduction of energy. The changes in geometry that result are either measured (analogously to the standard DIN 1999) or captured through the manufacture of a test part. A functioning test piece was engineered in the subproject.

A method for energy introduction into the machine tool that functions without any additional loading devices was engineered in conjunction with the test piece.

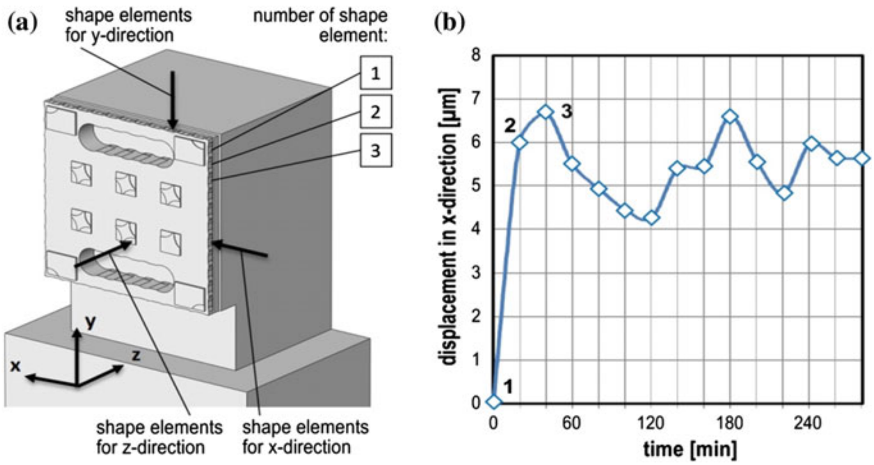


Fig. 20.6 Thermal test piece. **a** Test piece. **b** Thermal displacement

The relevant drives initiate a travel mode, which is carried out cyclically without the machining process. The travel mode has the same energetic effects as a representative machining process. The thermally induced machine tool displacements are transferred in shape elements on the test piece by means of a milling process.

At the beginning of the experiment associated with the test piece, test surfaces are milled in the test piece in the cold machine state. This process is run very quickly and thus virtually no thermally induced machine tool displacements occur during its performance. The thermally induced machine tool displacements generated during the experiment are transferred onto the test piece in defined time intervals. Figure 20.6 shows the test part with all 22 shape elements for the x-, y- and z-directions. Assuming 20 min intervals in the manufacturing sequence of the shape elements, it is possible to execute tests lasting 7 h.

The thermally induced machine tool displacements are found by scanning the test part afterwards in order to finally determine the displacement curves as a function of time depending on direction.

Process Quality (Variance)

Process quality specifies the repeatability with which the machining process can be conducted or the probability values at which special tolerances can be produced on the machine tool (Verein Deutscher Ingenieure 2002). Here only the thermally induced portion of process quality is taken into account. To quantify the process quality, the thermally induced dislocations are first determined for a certain quantity of workpieces by using the methods to investigate machining accuracy. This number is given by the productive machine running time with no breaks, as well as the part's machining time and thus, in turn, the technological application case depending on the operational constraints. Average, standard deviation σ and the process capability index C_P are calculated from the measured displacements of the individual tests (Weck 2006; DIN 1999).

Productivity

A machine tool's productivity can be quantified by the number of workpieces yielded per machine hour. Two tests are required to determine the curve of the thermally induced machine tool displacement as a function of time with different power consumption to warm up the machine tool in order to explore a method's influence on productivity by means of a test piece. It is possible to estimate the influence of increased part output on the maintenance of required tolerances. Based on the results, the number of ok parts and thus the process capability index C_P are derived for two different experimental conditions. Thus, the part output for this nominal value can be calculated based on the specification of a nominal process capability index value C_P of, for instance, 1, in a 6σ process, using the simplified assumption of an inversely proportional relationship between the process capability index C_P and part output. The productivity of these machine tool configurations can be benchmarked by comparing the part output values determined this way for different machine tool configurations.

Energy Consumption

Energy input is captured over the overall test period when determining the curve of the thermally induced machine tool displacements as a function of time. Energy consumption per workpiece can be found by means of the part output (see productivity). This value is used to assess the energy input of the machine tool configuration investigated. Benchmarks of the corresponding results for different machine tool configurations only make sense for the same technological application case (see Fig. 20.5). For an overall consideration of the methods' energetic impacts, for instance, on air conditioning of the factory floor that may not be needed, it is necessary to extend the benchmarking model using the relevant peripheral equipment.

20.2.3.2 Benchmarking Criteria Representing Costs

Expense benchmarking of the individual methods mainly analyses the costs, both in money and time, that occur as a result of the application of a compensation and correction method for each machine tool. It is assumed that the expenditures for the methods differ during the various life cycle phases of a machine (such as development, commissioning, operation). Consequently, a life cycle model for the representation of the relevant realm is used. The expenses (personnel and resource costs) accruing in each phase are analysed by means of process modelling languages [see for instance (Zur Muehlen and Indulska 2010)] in the form of workflow models. These models consider the corresponding circumstances (payload/salary, test capacities, opportunities to carry out simulations, etc.) of the machine tool producer, for which one of the developed methods is benchmarked, on the one hand. On the other hand, incoming information from the subprojects about the expenses to be expected in operation (e.g. for the modification of correction models) is also considered.

Machine Life Cycle Costs

Machine life cycle models represent every phase of the machine's creation, operation and recycling. The VDMA standard sheet no. 34160 presents detailed estimated costs based on a life cycle model (Verband Deutscher Maschinen- und Anlagenbau e.V. 2012). In the context of this project, these estimated costs are modified to identify relevant life cycle phases and are used, rather than merely understood purely as estimates. It is necessary to expand the guidelines for these estimated costs, since they only take into account the operator's view, though the methods also result in expenses for the machine tool manufacturers.

Figure 20.7 illustrates the modified guidelines for cost benchmarking and points out sections for each phase that are influenced by the methods according to the current state of expertise, which are thus analysed. In the "development phase", for instance, additional expenses in machine modelling and simulation result from the methods' application. Thus, it could be necessary, for example, to regularly adjust the correction models in the "operation phase", and these adjustments would

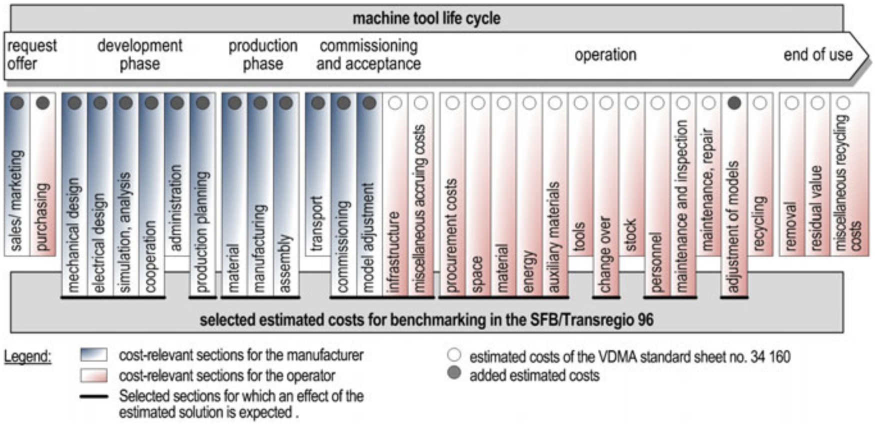


Fig. 20.7 Extended life cycle cost model with explicit focus on the correction or compensation methods

increase the maintenance and inspection costs. The phase “end of use” should not to be considered since it is relatively irrelevant.

From the current perspective, it is expected that additional expenses caused by the correction methods will be caused predominantly by personnel costs. Thus, for instance, experimental or model-based analyses of the thermal machine tool behaviour become necessary. The compensation methods mainly result in increased expenses for the purchase of components and semi-finished products.

The workflows related to the personnel costs are sophisticated and difficult to represent and define in terms of the resources and costs involved. For this reason, the workflows are analysed by means of workflow models.

Engineering Workflows

Modelling of workflows is performed by means of the process modelling language BPMN 2.0 [Business Process Management and Notation, compare (Recker 2008)]. The BPMN was modified for the domain (Braun and Esswein 2014) following an approach by Stroppi et al. (2011) so that resources and temporal or financial aspects of the specific workflows can be represented. A selection of the additional elements’ graphic representations is provided in Fig. 20.8. Non-graphic object attributes were also added.

The enquiry for the flow models is performed by interviews conducted regarding the workflows connected with the methods’ implementation and the expenses and times spent in the subprojects. The interviews are carried out repeatedly so that the states of progress that have changed due to the research outcomes can be mapped. Experts from industry are asked for their opinions on the solution methods’ consequences in practice based on these technology-specific flow models. These interviews are executed by means of the Delphi method to be able to, for instance, estimate expected expenses and required time in the operation phase. The flow

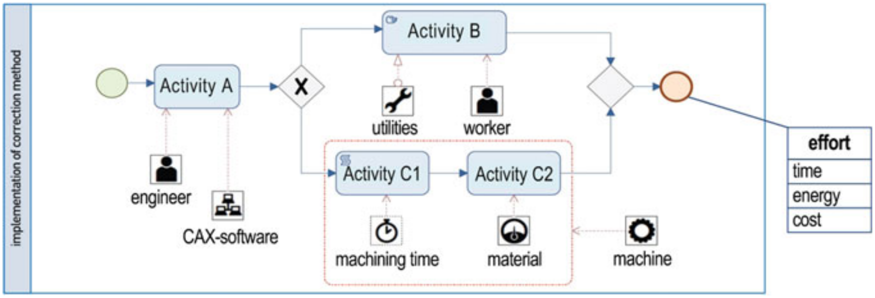


Fig. 20.8 Simplified BPMN model with extension elements (*screenshot* from the Meta modelling tool Cubetto Toolset). From *left* to *right* human resource (“engineer”), application/equipment (“CAX software”), time (“machining time”), auxiliary material, human resource (“worker”), material and machine

models are enhanced by this information. The flow models with the associated resource elements are created for each method (compare Fig. 20.8). In a second step, the parameter values of these models are assigned special values, such as for the number of employee hours required and hourly rates. Assignment of concrete data is done either based on the market prices or on business-individual cost.

It is possible to record the employee hours required per work step by means of the diary method (Rausch et al. 2012) and to estimate the values for the hourly rates or to take them from published wages. Thus it is possible to compare the solutions' methods.

20.3 Model Application

The model for technical-economic benchmarking of the methods to compensate and correct thermally induced machine tool errors is to be applied step by step depending on the research progress of the other subprojects. The analyses in the first phase of the CRC/TR 96 are initially focussed on the engineering-oriented issues of the correction methods. The benchmarking model is applied as mentioned below:

- Representation of the machine tool functions, including the methods applied to the partial model "machine tool configuration",
- Determination of the individual key performance indicators for benchmarking for the machine tool configurations: benefit key performance indicators to be found by means of the thermal test piece; as well as expense key performance indicators by means of workflow modelling,
- Bringing together the individual evaluations by weighed benchmarking of the suitability of the machine tool configurations for each reference case. Weighing makes it possible to consider different priorities resulting from the application cases in the machine properties' analysis. The weighed individual assessments are summarised at the end.

The individual benchmarking key performance indicators are concrete values representing, for instance, the accuracy that can be achieved with one method, related to one application case. Thus they are a means of support for the persons responsible for decision making. The weighed benchmark provides a total evaluation of a method implemented on a machine tool to obtain a rough overview by means of *one* key performance indicator.

20.4 Classification in the CRC/TR 96 and Outlook

In the current project step, the subproject's development flows related to the correction method are analysed so that the expenses incurred in their future industrial implementation can be estimated. Furthermore, these analyses make available expertise related to the different methods' economic and technical consequences for the subprojects for different reference cases. These, in turn, contribute to further enhancement of the methods and to the classification of fields of application in business as a whole.

The plan is to perform benefit analysis for the compensation and correction methods in later project phases, after they have been integrated into demonstrator machines and are thus available for testing.

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