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Multi-Criteria Decision Support for Manufacturing Process Chains

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Abstract: During the manufacturing planning, multiple variants of process chains for the manufacturing of a product to be developed are generated by engineers. In order to select an optimal variant, multiple decision criteria specifying technical, ecological and economical properties of the process chains as well as multiple assessments of different domain experts have to be taken into account. The contribution of this article is a two-step approach that provides a multi-criteria multi-expert assessment of manufacturing process chains supporting the selection of an optimal process chain. A web-based software tool that implements the multi-criteria assessment of process chains is also presented.

1 Introduction

The manufacturing planning takes place simultaneously with the embodiment design of a product to be developed [1]. During this planning, several variants of manufacturing process chains are developed that fit to the applicable manufacturing processes as well as the machine tools and work equipment available in a company. The selection of an optimal variant of a process chain has to consider a huge number of conflicting decision criteria [2,3]. On the one hand, the process chain should manufacture the product to be developed with low cost, low emissions as well as high quality and high resource and energy efficiency. On the other hand, the flexibility and adaptability of the process chain with regard to the available machine tools and the overall company objectives should be taken into account.

In order to assess the multiple decision criteria, several domain experts from material, product, process and factory planning as well as from controlling and marketing should be incorporated. Thus, the selection of an optimal process chain is a multi-criteria decision that requires the incorporation of multiple expert assessments.

In this article, a two-step approach for the multi-criteria assessment of variants of process chains is provided supporting the selection of an optimal variant. In the first step, the process chain variants are separately assessed with regard to technical, ecological and economical criteria. For these assessments, the multi-criteria decision

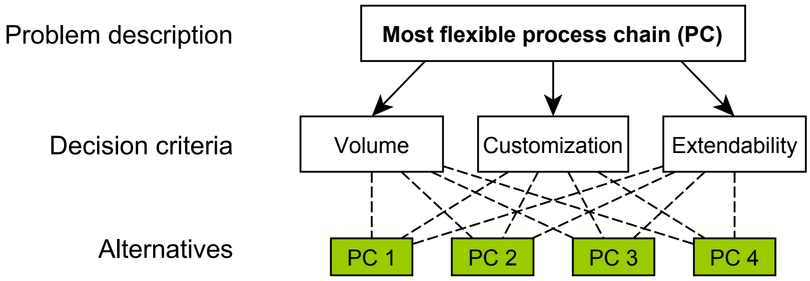

Figure 1: Example AHP criteria hierarchy and alternatives for an optimal alternative selection, which is choosing the most flexible process chain.

method Analytic Hierarchy Process (AHP) [4] and existing cost assessment approaches are applied. Assessments of different domain experts are incorporated. As a result, separate indicators quantifying the technical, ecological and economical suitability of the process chains for the company are provided. In the second step, an optimal process chain is selected by the domain experts.

The next sections are structured as follows: Section 2 summarizes the AHP. Section 3 presents the proposed two-step approach for the assessment of process chains. Existing approaches for the assessment of process chains are discussed in Sect. 4. Finally, Sect. 5 concludes.

2 The analytic hierarchy process

The analytic hierarchy process (AHP), initially proposed by Saaty [4], is a methodology which supports multi-criteria decisions in a widespread area of application, such as optimal alternative selection, prioritization [5], evaluation and benchmarking [6]. The AHP enables a calculation of ratio-scale weights from pairwise comparisons in a multi-criteria environment. In the following, the major steps of the AHP are explained in detail and an extension of AHP that uses fuzzy numbers for the pairwise comparisons is described.

2.1 Steps of AHP

Similar to other approaches for multi-criteria decision support, the AHP starts with the decomposition of the problem description into sub-problems, followed by comparative assessments with respect to sub-problems and ends with a synthesis of the assessments. Figure 1 depicts an example decomposition of an optimal alternative selection problem and the corresponding alternatives. In general, the AHP can be divided into five major steps.

1. **Problem decomposition and creation of a hierarchy of criteria:** The first step of AHP is the identification of the decision criteria of the overall problem and the creation of a hierarchy of the criteria. Each criterion may consist of several sub-criteria. Azani and Khorramshahgol [7] as well as Mendoza and Prabhu [8] suggest an independent gathering of prospective criteria by each expert, followed by the creation of the hierarchy in a joint meeting. A careful choice of experts is essential is this step, including ultimately affected experts stakeholders as well as experts with intermediary roles. This first step also includes the determination of possible alternatives.

2. **Pairwise comparisons:** After the identification of possible alternatives, the pairwise comparison of the alternatives with respect to criteria on the lowest level of the hierarchy and the pairwise comparison of (sub-)criteria with respect to their superior criterion in the hierarchy starts. As a result, multiple quadratic comparison matrices are created. In the example of Fig. 1, three 4x4 matrices, that contain the pairwise comparisons of the process chains with respect to the criteria *Volume* (flexibility of the output without adding new machines), *Customization* (geometric and material-related degree of freedom) and *Extendability* (effort for increasing the output by adding new machines) as well as one 3x3 matrix, that contains the pairwise comparisons of *Volume*, *Customization* and *Extendability* with respect to the overall selection problem, are created.

   Each pairwise comparison of two elements, which are either alternatives or criteria, is assessed on a scale from 1 to 9 proposed by Saaty. While an assessment of 1 expresses an equal importance of both elements compared, an assessment of 9 indicates that the first element is extremely more important than the second element. The reciprocal scale values $1/9$ to 1 are used to express that the second element is more important than the first element.

3. **Validation of the consistency of pairwise comparison matrices:** In an ideal assessment Equ. (1) should be valid for all matrices $A = (a_{ij}),\ i, j = 1,\ldots,n$ that are created in step 2 (n denote the matrix size).

$$a_{ij} = a_{ik} \cdot a_{kj} \quad i, j, k = 1,\ldots,n \tag{1}$$

   The rate of consistency of a matrix is measured by the consistency ratio CR proposed by Saaty. The CR is equal to zero for an ideal comparison matrix and greater than zero for inconsistent matrices. Saaty proposes a consistency be satisfying, if CR is less than 0.1.

4. **Calculation of local weights:** For each comparison matrix the local weights are calculated. A local weight specifies the assessment of a comparison object with

respect to the superior criterion in the interval $[0,1]$. The local weights are defined to be the values of the first eigenvector of the comparison matrix which is calculated based on the maximal eigenvalue of the matrix.

5. **Synthesis of global weights:** A global weight denotes the final weight of a criterion or alternative with respect to the overall decision problem. The global weight of a criterion c is defined to be the product of all local weights of the criteria on the path between c and the overall problem description i.e., the root of the hierarchy. The local weight of the root of the hierarchy is defined to be 1.

   The calculation of the global weight of an alternative is given in Equ. (2). For each criterion on the bottom level of the criteria hierarchy, the local weight of the alternative and the global weight of the corresponding criterion are multiplied. The intermediate results are summed up.

$$g_A = \sum_{c=1}^{m} w_{Ac} \cdot v_c \tag{2}$$

g_A global weight of alternative A

m number of criteria on the lowest level of the hierarchy

w_{Ac} local weight of alternative A with respect to criterion c

v_c global weight of criterion c

2.2 AHP assessment with fuzzy numbers

Policy making decisions of production planning are often based on experiences of domain experts and less appropriate data from external sources. Therefore, experts may be uncertain about the assessment of process chain alternatives for specific decision criteria and rather specify a possible interval for the pair comparison (e.g., a first process chain contributes 3 to 5 times more to the superior criterion than the second one) than a concrete assessment based on Saaty's scale as described in Sect. 2.1.

In order to incorporate such vague assessments in the AHP, fuzzy numbers are utilized for the pairwise comparison. In this article, we propose to use the approach of Buckley [9], in which a fuzzy number is defined to be the quadruple $(\alpha/\beta,\ \gamma/\delta)$ with $0 < \alpha \leq \beta \leq \gamma \leq \delta$. The quadruple defines a corresponding membership function which specifies the degree of truth (in an interval [0,1]) that an assessment is equal to a given value. While the degree of truth is defined to be zero for values lower or equal α (resp. greater or equal δ), the degree of truth linear increases from $\alpha = 0$ to $\beta = 1$ (resp. decreases from $\gamma = 1$ to $\delta = 0$). The degree of truth is defined to be 1 between β and γ. For example, the pair comparison for two alternatives of (1/2, 3/4) specifies that the first alternative is 1 to 4 times more important than the second one. If an expert believes that two alternatives are equal, the corresponding fuzzy number is (1/1, 1/1).

For the utilization of fuzzy numbers in the AHP, the calculation of local weights (step 4.) has to be adapted. According to Buckley, the local (fuzzy) weights are calculated by an adapted least square method. For a fuzzy comparison matrix $A = ((\alpha_{ij} / \beta_{ij},\ \gamma_{\mathrm{ij}} / \delta_{ij})),\ i, j = 1, \ldots, n$, he defines $\alpha_i = \prod_{j=1}^{n} \alpha_{ij}$ and $\alpha = \sum_{i=1}^{n} \alpha_i$. Similarly, $\beta_i, \beta, \gamma_i, \gamma, \delta_i$ and δ are defined. The local fuzzy weights $\overline{w_i}$ are calculated by $(\alpha_i \delta^{-1} / \beta_i \gamma^{-1},\ \gamma_{\mathrm{i}} \beta^{-1} / \delta_i \alpha^{-1})$.

3 Approach for the assessment of manufacturing process chains

This section provides the proposed approach for the assessment of manufacturing process chains. Section 3.1 presents the proposed approach supporting the selection of an optimal process chain. Section 3.2 provides an overview of the criteria hierarchies utilized for the assessment of technical and environment-related criteria with AHP. Finally, Sect. 3.3 outlines the web-based software tool for the multi-criteria assessment of manufacturing process chains.

3.1 Two-step approach

The proposed approach for the assessment of manufacturing process chains is structured in two main steps (see Fig. 2). In the first step the cost, technical and ecological criteria are assessed independently of each other. While for the assessment of cost common cost assessment methods are used (e.g., expert judgement, analogy costing), the AHP is applied for the assessment of technical and ecological criteria. The separate assessments result in independent indicators for the cost, the technical and the ecological criteria for each process chain.

In the second step, the three indicators of each process chain are presented to the decision makers in order to manually select the most appropriate process chain. To narrow down the number of process chains, all weakly dominated process chains are eliminated previously. According to the dominance strategy [10], a process chain A is weakly dominated by a process chain B, if B exceeds A in at least one indicator, while the other indicators of A are lower or equal than the indicators of B. Figure 2 illustrates the overall decision approach for an example assessment of three process chains. Another method supporting the final manual selection of an optimal process chain is the so-called Dreierkompromiss proposed in [2] that plots the three indicators

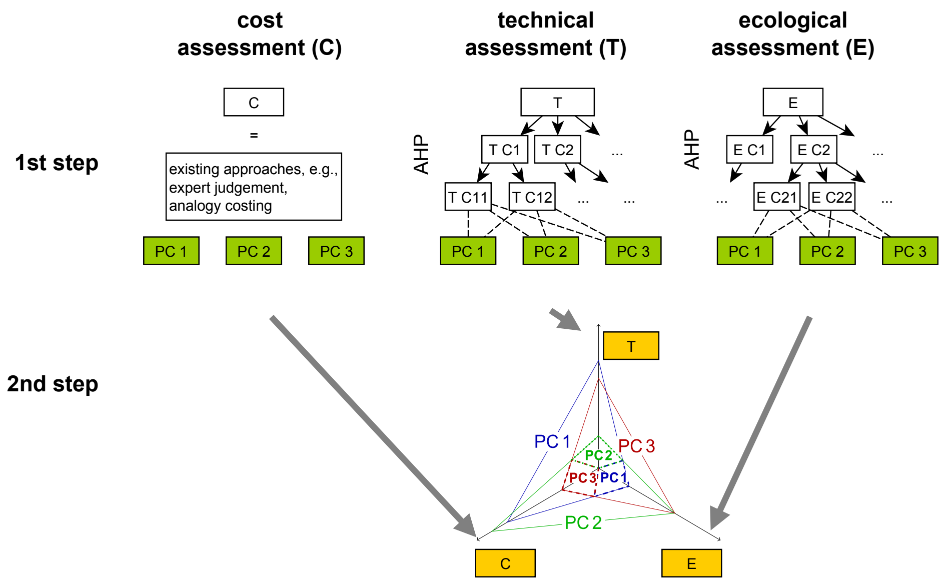

Figure 2: Multi-criteria decision approach for the assessment of process chains for an example with three process chains (PC 1, PC 2 and PC 3).

into a three-dimensional coordinate system. An optimal process chain is selected by calculating the minimal distance to an ideal process chain.

3.2 AHP hierarchies for the assessment of technical and ecological criteria

For the technical assessment of process chains, the major decision criteria are the *production time*, i.e. the timeframe from raw material provision up to the finished product, the *quality* of the finished product and the *suitability* of the process chain for the company (Fig. 3). While the production time is assessed by the REFA guidelines for process chain time measures [11], several sub-criteria are provided for the assessment of quality and company suitability.

The *quality* of a process chain is determined by the sub-criteria *reliability* of the process chain during the manufacturing process, *flexibility* of the process chain, *product quality* resulting and *post-treatment and waste* expected. The *flexibility* is further decomposed into the adaptability of the production *volume* without adding new machine tools, the geometrical and material-related *customization* of the product and the necessary effort to *extend* the process chain by additional machine tools.

The *company suitability* of the process chain for the company is determined by the effort for the implementation of the process chain (*pre-production requirements*), the necessary *logistics* during the manufacturing process as well as the demand for human resources (*staff requirement*) and the achievable *ergonomics* for the work force. Since

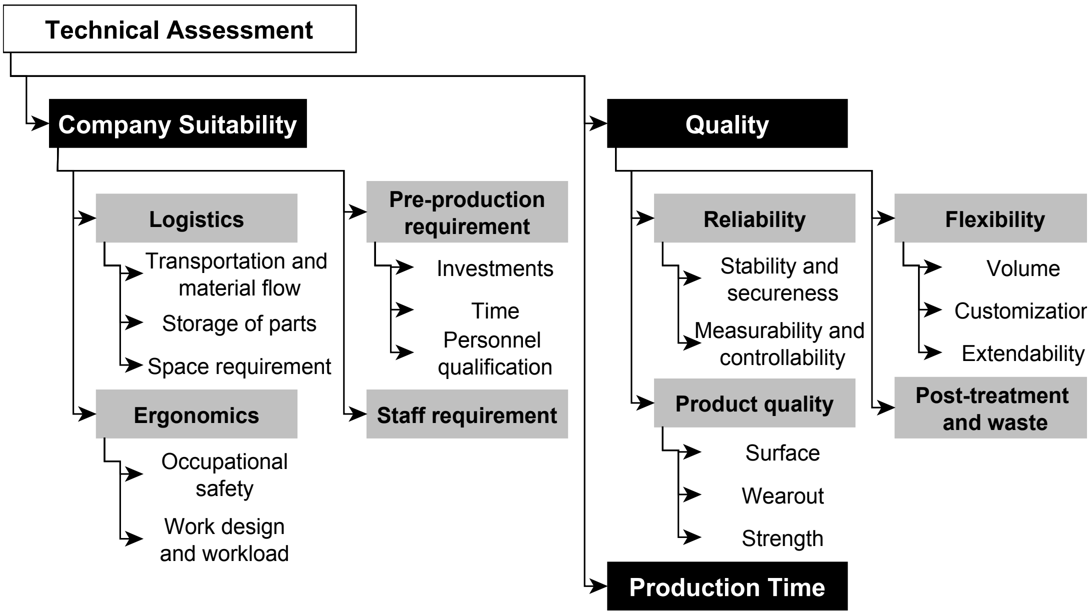

Figure 3: AHP hierarchy for the technical assessment of process chains.

the cost of a process chain is assessed independently, the sub-criteria of *pre-production requirements investments* and *personnel qualification* as well as the criterion *staff requirements* assess the organizational effort rather than costs.

Figure 4 depicts the criteria hierarchy for the ecological assessment of process chains. The major decision criteria are the *resource demand* and its efficient use (*resource efficiency*) as well as the *emissions* of the manufacturing process and the *recyclability* of working materials and the product itself.

In order to obtain reasonable assessments, a comparable life cycle view and a comparable scope of the process chains have to be taken into account, in particular for the ecological assessment. For example, a process chain A, which considers the manufacturing process from raw materials up to the final product, cannot be compared with a process chain B, which considers the manufacturing of semi-finished parts into the final product only. Therefore, the considered scope and the considered life cycle phases should match for each alternative assessed.

3.3 IT support for the assessment of process chains

In order to support the gathering and storing of pair comparisons, the synthesis of global weights as well as the incorporation of multiple stakeholders in the assessment

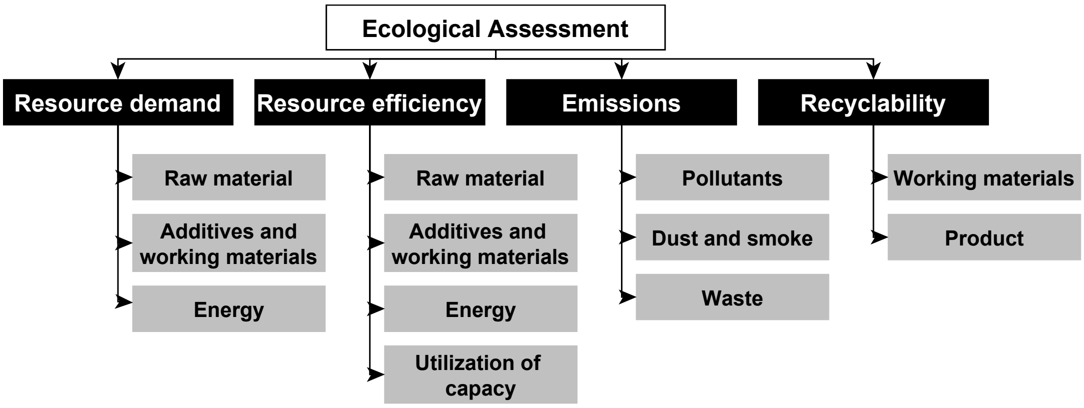

Figure 4: AHP hierarchy for the ecological assessment process chains.

process, IT support is feasible. We propose a web-based implementation for the multi-criteria assessment with AHP that utilizes the JBoss Middleware Suite[1], which provides a general basis for the development of Java-based web applications. The AHP Tool is part of a software framework called *EnergyNavigator* that incorporates several software tools to support engineers in developing energy efficient products [12]. The tool is designed as a general implementation of the AHP which can deal with arbitrary decision problems and, thus, is not restricted to the assessment of process chains. Figure 5 depicts the web-based user interface of the AHP tool.

In contrast to existing software tools, the AHP tool proposed provide the assessment with fuzzy numbers as proposed by Buckley [9] as well as the common assessment with the scale proposed by Saaty [4]. Furthermore, the tool provides an explicit group decision support in order to incorporate multiple domain experts in the assessment process. On the one hand, different experts can assess disjunct sets of decision criteria with each other. This so-called *partitioning strategy* is primarily used to reduce the amount of pair comparisons for individual experts and to transfer the assessment of decision criteria of a similar domain to the corresponding domain experts. On the other hand, a group of experts can assess the same set of decision criteria independently. The so-called *consensus strategy* is primarily applied to consolidate the accuracy of the assessment with respect to all experts. With that, the AHP tool provides an implementation of both strategies proposed in [5].

For the group decision support, the workflow management system jBPM and the corresponding workflow description language jPDL provided by the JBoss Suite are utilized. Participating experts of the overall assessment process are chosen by a project manager who is also responsible for determining the strategies and corresponding experts for the assessment of each criterion in the hierarchy. The lists of tasks assigned

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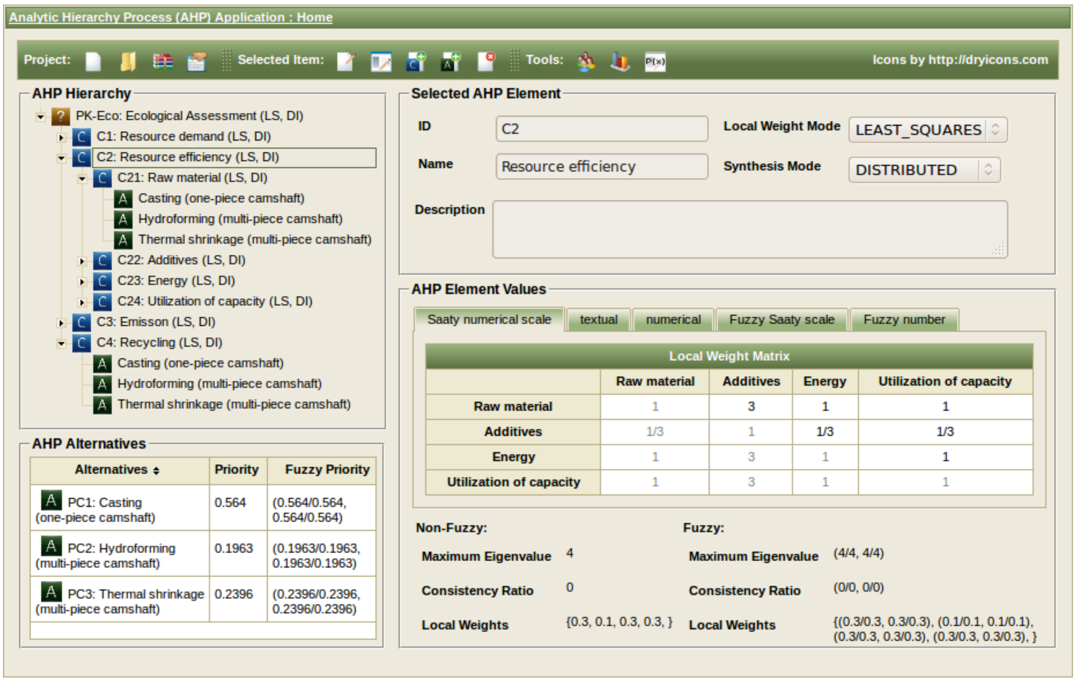
[1] http://www.jboss.org



	Raw material	Additives	Energy	Utilization of capacity
Raw material	1	3	1	1
Additives	1/3	1	1/3	1/3
Energy	1	3	1	1
Utilization of capacity	1	3	1	1

Figure 5: User interface of the web-based AHP software tool: criteria hierarchy for the ecological assessment (top left), properties of the selected hierarchy item (top right), comparison matrix of the selected item (bottom right), process chain priorities resulting (bottom left).

to each expert are managed by the workflow management system. The workflow system also generates tasks for the consensus process between experts.

The calculations of eigenvectors, eigenvalues, consistency ratios as well as the synthesis of global weights based on the pairwise comparisons are implemented as enterprise java beans which utilize the Java Matrix Package[2] to implement the basic linear algebra operations.

4 Existing approaches for the assessment of process chains

The production cost is an essential decision criterion for the assessment of alternative process chains. Therefore, several single criterion decision approaches are proposed that incorporates quantitative and qualitative decision criteria by considering their cost resulting only. In particular, the production time of a process chain is estimated by cost rates for working and machine hours. For example, Jacobs and Dürr [2] propose a so-called ambiguous production process graph, in which the maturity of the product is

[2] http://math.nist.gov/javanumerics/jama/

depicted by graph nodes and process steps by weighted graph edges. A weight of an edge corresponds to the cost of the process step. The costs are specified for a given number of pieces. The most favourable (i.e. cost-efficient) process chain corresponds to the path through the graph (source to sink) with lowest cost summed up.

Schmitt et al. [13] also propose such a single criterion approach that incorporates feature-based production cost as well as short- and non-short term cost related to the company and the environment.

Since an adequate assessment of the cost for the production time and environmental impacts is not always possible, several authors propose a pareto optimization approach for two and three criteria [2,14]. The criteria characteristics of the process chains are plotted in a two-dimensional (resp. three-dimensional) coordinate system. The most favourable process chain is determined by the minimum geometric distance between the characteristics of the process chain and an ideal process chain that is generated from the optimal values of the considered criteria. However, the authors state, that such geometrical approaches are applicable for at most three criteria.

The selection of the most favourable process chain from a set of alternatives often requires the incorporation of environmental and company-specific criteria in addition to production time and cost. Therefore, decision approaches for more than two or three criteria seems more appropriate for a detailed assessment of process chains.

Trommer [15] proposes an assessment approach for process chains based on the fuzzy analytic hierarchy process (fuzzy AHP) of Buckley [9]. Instead of using a discrete number from Saaty's scale to compare the alternatives, fuzzy sets that describe an interval of numbers from Saaty's scale, are used for the pairwise comparisons to incorporate uncertainty in the assessment explicitly. Trommer utilizes the criteria cost, time, quality, company-fit, ecology as well as a wide range of sub-criteria to select the most favourable process chain out of a set of alternative process chains. Since the AHP as well as the fuzzy AHP are based on the assumption of independent criteria, the proposed incorporation of the criteria cost and time in the same hierarchy is arguable. Besides, the utilization of fuzzy sets requires additional effort for the pairwise comparisons and not necessarily results in a defined ranking. The AHP already provides a smooth assessment due to the textual description of Saaty's scale items and inconsistent comparisons [16]. Furthermore, the stability of the final ranking with respect to modifications of pairwise comparisons can also be evaluated with sensitivity analysis methods for the AHP.

Similar to the partial models of the approach proposed in Sect. 3, Müller [14] proposes the partial models production cost, quality of the process chain, and one-off expenses for the launch of process chains. While the production cost and the one-off expenses are calculated by using cost calculation approaches, the quality of a process chain is assessed with the cost-utility analysis. However, the applicability of the cost-utility analysis for the assessment of qualitative criteria is restricted [17].

Schmidtner [3] proposes a criteria hierarchy for the assessment of process chains and suggest the usage of the cost-utility analysis for the entire hierarchy. Since the cost-utility analysis requires the independence of decision criteria, it is arguable, whether his proposed incorporation of cost, production time, quality, and ecological criteria results in an accurate assessment.

Spengler et al. [18] suggest the PROMETHEE method for evaluating tinplate manufacturing processes, since the method enables the incorporation of incomparable alternatives in the decision process and contains the *concept of weak preference* to declare that an alternative is just slightly better than another. However, we found that all criteria considered are comparable and that the concept of weak preference is implicitly included in the AHP due to the ratio-scale measurement. Besides, the global weights of the AHP specify how much an alternative is favored over another alternative instead of the non-cardinal order resulting from PROMETHEE.

In addition to multi-criteria decision approaches, multi-objective decision approaches are utilized if an unlimited number of alternatives is considered. Therefore, a set of goal functions for the corresponding criteria has to be maximized. For example, Alexander et al. [19] utilize the goal programming approach for the assessment of nitric manufacturing processes and Denkena et al. [20] propose a holistic approach that combines genetic programming with pareto analysis for the optimization of entire process chains. However, multi-objective decision approaches rather focus on the improvement of a given process chain than the comparison of different process chain alternatives. Besides, the approaches are based on a detailed mathematical description of processes and process parameters which are often not available in early production planning stages.

5 Conclusion

The assessment of manufacturing process chains has to consider multiple and potentially conflicting decision criteria. Besides the common technical and economical decision criteria, special ecological decision criteria, such as resource and energy efficiency, have to be taken into account. The proposed approach for the assessment of process chains provides such a multi-criteria decision support based on the Analytic Hierarchy Process. Due to the criteria hierarchies for the technical and ecological assessment of process chains presented, assessments with respect to multiple single decision criteria are aggregated forming separate indicators that quantify the technical and ecological suitability of a process chain.

Engineers are faced with multi-criteria decisions, especially the selection of optimal variants, in several steps of product development and manufacturing planning. Thus, future work focus on adapting of the proposed two-step approach to other multi-criteria decision problems of product development, such as the assessment of early product designs.

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