



A multi-criteria decision analysis approach for evaluating production technology in battery cell manufacturing

Tim Wicke^{a,b},* , Christoph Neef^a, Jens Tübke^{b,c,d}

^a Fraunhofer Institute for Systems and Innovation Research ISI, Breslauer Str. 48, 76139, Karlsruhe, Germany

^b Institute of Mechanical Process Engineering and Mechanics (MVM), Karlsruhe Institute of Technology, Kaiserstraße 12, 76131, Karlsruhe, Germany

^c Fraunhofer Research Institution for Battery Cell Production FFB, Bergiusstraße 8, 48165, Münster, Germany

^d Fraunhofer Institute for Chemical Technology ICT, Joseph-von-Fraunhofer-Straße 7, 76327, Pfinztal, Germany

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ABSTRACT

The rapid global expansion of lithium-ion battery manufacturing requires systematic methods to compare and evaluate established and innovative production technologies. This paper develops a multi-criteria decision analysis approach to assess process equipment along four dimensions: cost, throughput, quality and sustainability. Ten criteria are defined, derived from a literature review. Building on these criteria, PROMETHEE II is selected as a suitable multi-criteria decision analysis method and adapted to the battery manufacturing context. The adaptations include exclusion criteria for minimum performance requirements, modelling of parameter uncertainty via Monte Carlo simulation, tailored preference functions for different criteria, and a user-specific weighting scheme reflecting different stakeholder priorities. The evaluation method is illustrated in a case study comparing knife and laser slitting of electrodes. The case study shows that advantages, such as improved quality, must always be weighed against disadvantages, such as higher investment costs. A tipping-point analysis demonstrates how the method can translate abstract trade-offs into concrete technological or economic targets, e.g., required cost reductions. The proposed approach provides a transparent, flexible decision-support framework for selecting production technologies and for guiding R&D and investment priorities in battery cell manufacturing.

1. Introduction

Global demand for lithium-ion batteries (LIB) continues to grow. From around 1.6 TWh in 2025, demand is projected to reach 2.6–4.5 TWh by 2030 [1]. Announced capacity additions amount to roughly 8.5 TWh by 2030 [1]. Despite discounting announcements [2] but considering replacement cycles of 6–8 years [3], hundreds of new production lines (typically with throughputs between 5 and 10 GWh/a [4]) are expected, creating room for process innovation. Such innovation is needed to improve the quality of products and processes, reduce energy demand and greenhouse gas emissions, and, in certain cases, enable new product designs.

A range of methodological approaches has been established to evaluate battery production. Techno-economic process-based cost models [3,5–8] provide detailed cost decompositions. Life cycle and energy-flow models [9–16] quantify energy and emissions for battery production, but rarely integrate cost. Recent cross-dimensional frameworks [17–20] direct or indirect combine perspectives without aggregating them into a final ranking or decision, e.g. via multi-criteria

decision analysis (MCDA). MCDA exist in adjacent areas of the battery field, e.g. for stationary grid storage [21], for battery chemistries in electric vehicles [22], and at the cathode material level [23], but they have, to the best of our knowledge, not yet been transferred to the evaluation of production equipment.

In this study, we propose a structured MCDA approach to evaluate production technologies across costs, quality, throughput and sustainability, closing this gap. We aim to translate the technical characteristics of production equipment into a consistent set of evaluation criteria. This makes the trade-offs between alternative process technologies explicit and comparable. The main contribution of this work is the development and adaptation of an MCDA for the technology evaluation. A case study on slitting serves as an illustration of the method. Detailed technical modelling and parameterisation are relegated to the supplementary material.

Throughout the development, we prioritise a methodological approach that can be applied in industrial and research contexts with reasonable effort while remaining grounded in scientific input. The applications are wide-ranging. For example, cell manufacturers must

* Corresponding author at: Fraunhofer Institute for Systems and Innovation Research ISI, Breslauer Str. 48, 76139, Karlsruhe, Germany.
E-mail address: tim.wicke@isi.fraunhofer.de (T. Wicke).

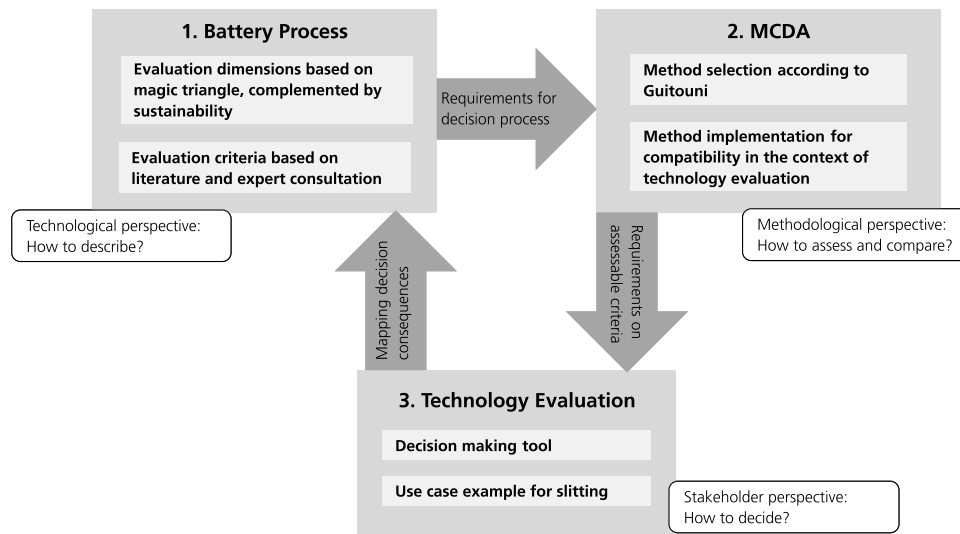


Fig. 1. Core elements for developing the technology evaluation method.

decide which process alternative to implement when building new factories, balancing, e.g., costs with current and future requirements regarding the carbon footprint of their products. From a policy perspective, the question is which process technologies should be prioritised in R&D and investment funding so that domestic industry can compete effectively with future foreign low-energy-consumption gigafactories. Many other related questions are conceivable.

2. Method

The evaluation process developed in this work defines four dimensions and ten criteria for a holistic assessment of battery production technologies. Based on this framework, we select and adapt a suitable MCDA method for the battery manufacturing context. This development comprises three interlinked steps: (1) a comprehensive description of process technologies along economic, ecological, and technical dimensions, (2) the identification and adaptation of an MCDA method for battery production and (3) the application of the method to practical decision problems with differing requirements (see Fig. 1).

2.1. Evaluation dimensions

For a comprehensive evaluation of production technologies, several dimensions D must be considered. In technology and project management, the so-called magic triangle of costs (D_1), time, and quality (D_3) is often used to capture key trade-offs [24–26]. In our context, the time dimension is operationalised as production throughput (D_2). These three aspects form the core of our evaluation framework. Ecological aspects, which are increasingly important in battery production [27], are not covered by the classic triangle. We therefore add sustainability as a fourth dimension (D_4), including environmental and, where appropriate, social aspects [28].

2.2. Evaluation criteria

In practical application, the four dimensions must be operationalised through suitable, preferably measurable, variables. We therefore define evaluation criteria C that capture the most relevant characteristics of production equipment. To identify these criteria, we conducted a literature-based review of commonly used variables to describe technologies in battery cell production (see Section 3.2.1). As this study focuses on individual process steps and machines, we only considered literature analysing cell production on a plant parameter basis. The criteria identified in the literature were complemented by two additional criteria to ensure balanced coverage of all four dimensions (Section 3.2.2).

2.3. Multi-criteria decision analysis

MCDA identifies a preferred option from a set of predefined alternatives based on multiple criteria. As we compare a finite set of production technologies using cardinal information, multi-attribute decision-making (MADM) is appropriate [29].

After filtering candidate methods by the type and quality of available information (see S1), we applied the selection guidelines of Guitouni and Martel [30], which are considered suitable for selecting a specific MADM method for a defined use case [31,32].

2.4. Method adaptation

PROMETHEE was identified as the most suitable MCDA approach. To meet the specific requirements of multi-criteria evaluation of battery production technologies (Section 2.5), we adapt the standard PROMETHEE II method. The adaptation concerns (1) the introduction of exclusion criteria, (2) the modelling of parameter uncertainties, (3) the choice of appropriate preference functions, and (4) the weighting of criteria.

2.5. Requirements for the evaluation approach

Different requirements apply to the evaluation criteria as well as the decision method for evaluating battery production technology, as described in this study:

The evaluation dimensions and evaluation criteria should be general in scope to cover all relevant aspects of production technologies, while allowing flexible prioritisation through weighting.

The method should be applicable in both industry and research contexts, from laboratory or pilot scales to full-scale manufacturing. In doing so, the evaluation process must be conducted by a single decision-maker without time-consuming group processes.

The approach should support the evaluation of individual process steps as well as process chains. Both the comparison of equipment within the same technology and between alternative technologies, including impacts on upstream and downstream steps must be enabled.

Uncertainties in technical specifications, especially for innovative production equipment, must be addressed. Where no empirical data are available, assumptions with appropriately larger uncertainty ranges are required.

Table 1
Structure of the supplementary material.

Section	Content
S1	Classification of MADM methods by type and quality of available information and application of the Guitouni and Martel guidelines to the candidate methods (MAVT, AHP, PROMETHEE, ELECTRE).
S2	Mathematical foundations of PROMETHEE I and II as well as selection of suitable preference function from the six PROMETHEE function types. Introduction of used uncertainty modelling.
S3	Calculation formulas for evaluation criteria, including the characteristic lists used for the checklist-based criteria.
S4	Input parameters for the case study (knife slitter, laser slitter, and shared general parameters).
S5	Computed criterion values for the slitter alternatives of the case study.

2.6. Structure of the supplementary material

The detailed mathematical foundations, formulas, parameter values and case study calculations supporting the method described above are provided in the supplementary material. To preserve the readability of the main text, technical details are referenced where relevant rather than being reproduced in full. Table 1 summarises the content of each section of the supplementary material.

3. Results

3.1. Evaluation dimensions

The four dimensions cost (D_1), throughput (D_2), quality (D_3), and sustainability (D_4) capture the key trade-offs in battery cell production. Costs and throughput determine economic competitiveness in a market characterised by overcapacity and price pressure [33,34]. Quality has gained attention due to high scrap rates during ramp-up and associated financial risks [4,35], and is even regulated [36]. Sustainability requirements are being tightened by new regulations [27].

3.2. Evaluation criteria

3.2.1. Literature for process technology analysis

We examined 30 studies to identify common evaluation criteria for battery production technologies. Only two of them consider all four dimensions defined in our work quantitatively. For example, Krätzig and Degen [20] analyse multiple aspects in a cross-dimensional framework that closely aligns with our criteria. Knehr et al. [18] as well as Lechner et al. [19] indirectly cover several dimensions as part of a cost analysis. Degen and Krätzig [17] propose a process-oriented methodology for technology selection in the early stages of development. Most other studies focus on individual aspects within a single dimension. Table 2 summarises which dimensions are quantified in each study and points out the level of detail.

Cost models for battery cells frequently differentiate investment and operational costs at the machine or process level [3,5,7,8,11,18–20,44,46,48–50]. Most studies rely on assumptions, particularly for operational costs. Throughput is typically derived from machine parameters and product specifications [7,10,11,18–20,46–49]. Quality is represented by scrap, defects and control measures [6,7,18–20,37,38,41,43,45–48,51]. Sustainability is mostly assessed via energy consumption and CO₂ emissions, often in LCA contexts [9–16,20,39,45].

While innovative production technologies are discussed in [17,42,43,52,53], a systematic, holistic evaluation balancing criteria based on quantitative numbers and yielding a final selection has rarely been described.

3.2.2. Defined evaluation criteria

Seven criteria were adopted directly from the literature discussed in Section 3.2.1. One criterion was only briefly mentioned and two additional criteria were introduced to close gaps in the evaluation framework.

C_1 Maximum throughput is a key machine parameter commonly used to characterise production lines by their theoretical annual output (GWh/a). It is either specified directly on equipment data sheets or calculated from machine parameters and product assumptions, as is common practice in the literature [6,7,10,11,18–20,46–49]. The criterion belongs primarily to the throughput dimension (D_2), but also affects cost (D_1) via economies of scale.

C_2 Scrap denotes production waste arising from unavoidable processes (e.g. edge trim) and from quality-related rejects at electrode or cell level. Scrap rates can only be measured under operating conditions and strongly depend on process design and stability. Scrap rates are especially high during ramp-up [54–56]. After ramp-up, production facilities are optimised for a specific operating point. Any deviation from this usually results in higher scrap rates. Different process steps exhibit different scrap sensitivities. In particular, the coating and drying steps cause high scrap rates [5,7,41,56]. The literature provides estimates of unavoidable production waste (e.g. from cutting) and assumptions regarding the amount of scrap generated by different process steps [18,19,41,57]. Scrap is expressed as a percentage value relative to the total output. It is a central quality (D_3) parameter, but also impacts sustainability (D_4), throughput (D_2), and cost (D_1).

C_3 Production output is the amount of cells or semi-finished products under realistic operating conditions. It is influenced by the upstream and downstream production processes. Scrap and machine downtimes are subtracted from the maximum production throughput. Downtimes arise from maintenance, batch or coil changes, and less than full capacity utilisation. Production output can be calculated from target process parameters. For productions that are not in operation yet, this requires assumptions. The criterion is relevant for multiple dimensions. Together with maximum throughput it characterises the throughput dimension (D_2). Due to the scaling effects and through higher efficiency per cell produced, the output also affects costs (D_1). On top, energy consumption and thus sustainability (D_4) are affected.

C_4 Energy consumption is divided into electrical and thermal energy demand. Innovative production technologies often claim lower energy use than the state-of-the-art. In addition, the shift from fossil energy carriers to electricity is desirable in order to reduce dependence on fossil fuels. Total energy consumption is calculated from the machine operating time and specific power demand, and is related to the production output (kWh energy consumption per kWh battery capacity produced). Nominal power ratings in data sheets or installation loads often reflect maximum power, not typical operating consumption. Until measurement data are available, we have to rely on assumptions. Some studies distinguish between fossil-based and electricity-based consumption [3,9,11,12,14,18,49]. Others report total energy use [5,13,15,16,19,20,39,40,42,45]. Energy consumption particularly affects the sustainability dimension (D_4), but is also a cost driver (D_1).

Table 2
Literature overview within different evaluation dimensions.

Publication	Year	Cost	Throughput	Quality	Sustainability
Brodd & Helou [37]	2013	●	○	●	○
Westermeier et al. [38]	2013	○	○	●	○
Nelson et al. [6]	2015	●	●	●	○
Sakti et al. [8]	2015	●	●	●	○
Ciez & Whitacre [5]	2017	●	●	●	●
Pettinger & Dong [39]	2017	○	○	○	●
Yuan et al. [40]	2017	○	○	○	●
Nelson et al. [7]	2019	●	●	●	○
Thomitzek et al. [15]	2019	○	○	○	●
Thomitzek et al. [16]	2019	○	○	○	●
Sun et al. [14]	2020	○	○	○	●
Chordia et al. [9]	2021	○	○	○	●
Duffner et al. [3]	2021	●	○	○	●
Jinasena et al. [13]	2021	○	○	○	●
Kehrer et al. [41]	2021	○	○	●	○
Liu et al. [42]	2021	●	○	○	●
Mauler et al. [43]	2021	●	●	●	○
Mauler et al. [44]	2021	○	○	●	○
Wessel et al. [45]	2021	○	○	●	●
Degen & Schütte [10]	2022	○	●	○	●
Knehr et al. [46]	2022	●	●	○	○
Li et al. [47]	2022	○	●	●	○
Degen et al. [11]	2023	○	●	○	●
Degen [12]	2023	○	○	○	●
Heimes et al. [48]	2023	●	●	●	○
Degen & Krätzig [49]	2024	●	●	○	●
Degen & Krätzig [17]	2024	○	○	●	○
Knehr et al. [18]	2024	●	●	●	●
Lechner et al. [19]	2024	●	●	●	●
Krätzig & Degen [20]	2025	●	●	●	●

○ = not addressed ● = qualitative or brief consideration ● = quantitative evaluation.

C_5 CO₂ emissions are closely linked to energy consumption, but depend on the energy carrier mix (e.g. renewable energies or fossil fuels). With electricity from renewable sources, electricity-based processes can achieve low emission values. The CO₂ footprint (g CO₂ per kWh) is a central metric in battery regulations [27]. Some studies estimate emissions using regional emission factors for electricity generation and heat supply from the LCA literature [58–63]. The literature seldom quantifies CO₂ emissions at the level of individual production machines. Only few studies calculate CO₂ emissions for individual process steps [10,20]. CO₂ emissions are primarily assigned to the sustainability dimension (D_4). But, similar to energy use, there is an overlap with cost aspects (D_1), due to CO₂ pricing and taxes.

C_6 Investment costs are a relevant decision criterion in machinery procurement. For better comparability, investment can be stated per unit of annual production capacity (EUR/(GWh/a)) so that it reflects machine throughput via normalisation. Besides the purchase price, installation costs and infrastructure-related costs (e.g. footprint, dry-room or clean-room requirements) can be included. Cost assumptions in the literature are based in part on price information provided by machine manufacturers. Partly they are also based on expert assessment [3,5–8, 10,18–20,46,48].

C_7 Operational costs of production directly influence cell production costs and are therefore essential in technology evaluation. The relative importance of acquisition costs vs. operational costs in procurement decisions is frequently debated. Operational costs summarise depreciation of equipment, capital, building and infrastructure costs, energy costs, spare parts and labour costs in running costs per kWh produced. Literature often relies on assumed values for these components [3,5,8, 10,19,37,64]. Due to economies of scale and the influence of energy use, investment costs and operational costs depend on throughput. Operational costs is additionally related to sustainability. Both criteria form the core of the cost dimension (D_1).

C_8 Manufacturing quality emerges from the literature as a central aspect of battery production. Compared to the production losses themselves (see C_2), manufacturing quality captures the underlying capability of the manufacturing process and control measures to meet

specified tolerances. We found no systematic comparisons of production technologies based on quality, although there are hundreds of process variables, many of which are critical for product quality [65–67]. For each process step and machine alternative, quality-relevant characteristics and tolerances, as well as (inline) inspection measures, can be identified. Due to the large number of parameters, the literature provides no comprehensive overview across all process steps. Only partial examples exist, e.g., for calendaring [66]. Otherwise, only individual quality aspects, not intended to be complete, are mentioned [38, 47,48].

We operationalise the criterion via Equation S18, resulting in a dimensionless score. The list of relevant characteristics can be extended by expert knowledge for each process step. Together with scrap, this criterion is important for assessing the total quality of the production equipment and is therefore assigned to the quality dimension (D_3). As higher quality requirements often require more advanced machinery, additional process controls and monitoring, it also affects costs (D_1).

C_9 Criticality & social aspects in existing literature mostly focus on raw materials [68,69], not the cell production process itself. We found no studies that systematically consider social aspects such as occupational safety at the process step level. Yet these aspects form the interface between machines and factory personnel as well as the factory's surroundings and are governed by occupational safety and environmental legislation [70,71] as well as environmental aspects (e.g. emission control laws) [72]. We therefore include a dedicated criterion, covering worker health and safety risks and local environmental impacts (e.g. hazardous auxiliaries).

It is calculated using Equation S18 as well, resulting in a dimensionless score. The set of relevant characteristics can be compiled individually for each process step, based on practical production experience. Examples include the use of toxic substances or the presence of significant health risks for workers. Applicable safety classifications are provided by regulations and standards [70,73]. The criterion is assigned to the sustainability dimension (D_4).

C_{10} Fit & flexibility was not described in the screened literature. We introduce Fit & flexibility to assess (1) compatibility with upstream and

Table 3
Literature overview within the defined evaluation criteria.

Publication	Year	Maximum throughput	Scrap	Production output	Electrical energy demand	Gas energy demand	Energy demand	CO ₂ emissions	Investment costs	Operational costs	Manufacturing quality	Fit & flexibility	Criticality & social aspects
Brodd & Helou [37]	2013	○	●	○	○	○	○	○	○	●	○	○	○
Westermeyer et al. [38]	2013	○	○	○	○	○	○	○	○	○	○	○	○
Nelson et al. [6]	2015	●	●	●	○	○	○	○	○	○	○	○	○
Sakti et al. [8]	2015	○	●	●	○	○	○	○	○	○	○	○	○
Ciez & Whitacre [5]	2017	○	●	●	○	○	○	○	○	○	○	○	○
Pettinger & Dong [39]	2017	○	○	○	○	○	○	○	○	○	○	○	○
Yuan et al. [40]	2017	○	○	○	○	○	○	○	○	○	○	○	○
Nelson et al. [7]	2019	●	●	●	○	○	○	○	○	○	○	○	○
Thomitzek et al. [15]	2019	○	○	○	○	○	○	○	○	○	○	○	○
Thomitzek et al. [16]	2019	○	○	○	○	○	○	○	○	○	○	○	○
Sun et al. [14]	2020	○	○	○	●	●	●	○	○	○	○	○	○
Chordia et al. [9]	2021	○	○	○	●	●	●	○	○	○	○	○	○
Duffner et al. [3]	2021	○	○	○	○	○	○	○	○	○	○	○	○
Jinasena et al. [13]	2021	○	○	○	○	○	○	○	○	○	○	○	○
Kehrer et al. [41]	2021	○	●	○	○	○	○	○	○	○	○	○	○
Liu et al. [42]	2021	○	○	○	○	○	○	○	○	○	○	○	○
Mauler et al. [43]	2021	○	●	●	○	○	○	○	○	○	○	○	○
Mauler et al. [44]	2021	○	●	○	○	○	○	○	○	○	○	○	○
Wessel et al. [45]	2021	○	●	○	○	○	○	○	○	○	○	○	○
Degen & Schütte [10]	2022	●	○	○	●	●	●	○	○	○	○	○	○
Knehr et al. [46]	2022	●	●	●	○	○	○	○	○	○	○	○	○
Li et al. [47]	2022	○	○	○	○	○	○	○	○	○	○	○	○
Degen et al. [11]	2023	●	○	○	●	●	●	○	○	○	○	○	○
Degen [12]	2023	○	○	○	●	●	●	○	○	○	○	○	○
Heimes et al. [48]	2023	●	○	○	○	○	○	○	○	○	○	○	○
Degen & Krätzig [49]	2024	●	○	○	●	●	●	○	○	○	○	○	○
Degen & Krätzig [17]	2024	○	○	○	○	○	○	○	○	○	○	○	○
Knehr et al. [18]	2024	●	●	●	●	●	●	○	○	○	○	○	○
Lechner et al. [19]	2024	●	●	●	○	○	○	○	○	○	○	○	○
Krätzig & Degen [20]	2025	●	●	○	○	○	○	○	○	○	○	○	○

○ = not addressed ● = qualitative or brief consideration ● = quantitative evaluation.

downstream process steps, (2) fit to the planned product, and (3) alignment with the regional implementation context. Product compatibility is increasingly important due to the growing diversity of cell formats and chemistries, especially in automotive applications [74]. If order volumes are below the capacity of a single line, production of different orders on a single production line requires flexible equipment. Experience from large-scale European projects also highlights the importance of regional customer support and familiarity with local regulations.

These aspects are captured in a fit & flexibility score, calculated from individual characteristics via Equation S18, resulting in a unitless value, and extended by an additional operational flexibility term (see Equation S19). Because there is limited literature on this topic, relevant characteristics must be compiled by practitioners based on their experience. For system compatibility, some work on (digital) interfaces in battery production is available [75–78]. Fit & flexibility is primarily assigned to the quality dimension (D_3) but also affects costs (D_1), as higher flexibility often entails higher investment and complexity.

Table 3 provides an overview of the identified literature, categorised according to the defined evaluation criteria. Criteria C_1 to C_7 can be summarised as data-based criteria, while C_8 to C_{10} are checklist-based criteria. Data-based criteria are calculated directly from numerical process parameters I such as throughput, scrap rates, energy consumption or costs. Checklist-based criteria are not measured by a single physical quantity, but are obtained from checklists of binary characteristics B (e.g. fulfilment of specific quality controls, safety or environmental measures, and interface or flexibility requirements). Calculations for all criteria can be found in S3.

3.3. Selection of a multi-attribute decision making method

Based on the framework conditions and the ten evaluation criteria, we pre-selected four suitable methods (MAVT, AHP, PROMETHEE, ELECTRE) due to the availability of cardinal information for every criterion. Applying the assessment guidelines of Guitouni and Martel [30], PROMETHEE emerged as the most suitable MADM method. Of their seven guidelines, five are relevant in our context. The preselection steps and key questions are detailed in S1. The results of the analysis are shown in Table 4.

Using these pairwise comparisons and the resulting preference values between all alternatives, PROMETHEE II computes for each option a so-called net flow ϕ^0 (see S2), which summarises its overall preference relative to the others. Alternatives are then ranked in descending order of the value.

3.4. Implementation of PROMETHEE

For the practical application of PROMETHEE as a technology evaluation method, several method components are implemented and adapted. The PROMETHEE method itself is described in more detail in S2. Here, we focus on exclusion criteria, uncertainty modelling, preference functions and weighting.

Exclusion criteria. PROMETHEE enables different options to be assessed and ranked. However, there are some minimum requirements for the process and equipment selection in the cell manufacturing application case. Available equipment that fails to meet these requirements are excluded a priori from the evaluation. Minimum requirements concern,

Table 4
Relevant guideline conditions according to Guitouni and Martel [30].

Requirements for method selection	MAVT	AHP	PROMETHEE	ELECTRE
(1) single decision-maker	x	x	x	x
(2) pairwise comparison		x	x	x
(3) rank order	x	x	x	x
(5) partial compensation			x	x
(6) transparency of the solution process	x	x	x	

in particular, minimum throughput, plant compatibility and manufacturing quality. In brownfield projects, compatibility constraints are especially strict, and process and product must be mutually compatible. Otherwise the process is not fit to produce the required quantity and specification. Minimum throughput is checked using the calculated production output. For each process step, quality-related characteristics (manufacturing quality) and plant compatibility characteristics (fit & flexibility) can be specified individually (see S3) to define exclusion thresholds.

Uncertainties and modelling. Uncertainties arise in the calculation of all criteria. For data-based criteria (C_1 - C_7), they mainly result from missing performance data I under real operating conditions. Examples of this include product-dependent energy use, electricity prices or project-specific cost assumptions. For checklist-based criteria (C_8 - C_{10}), there is a risk that important characteristics B may have been incorrectly prioritised or omitted. To quantify these uncertainties, the methodological approach allows the user to specify plausible ranges for the criteria input. We incorporate uncertainty (u) externally to PROMETHEE via probabilistic modelling (Monte Carlo) [79]. A percentage deviation is assigned to each input parameter I for the data-based criteria. The base uncertainty $u_1 \in (0, 1)$ captures general parameter variability (e.g. electricity price fluctuations). Two additional factors account for data accuracy (u_2 , e.g. missing technical data sheet information) and process innovativeness (u_3 , immaturity of technologies not yet available at giga-scale). This distinction enables well-known, well-documented technologies ($u_2 = u_3 = 1$) to be distinguished from innovative options with sparse data ($u_2, u_3 > 1$). The combined uncertainty defines the sampling range for each input parameter ($u_I = u_1 \cdot u_2 \cdot u_3$). For the checklist-based criteria, we model the uncertainties using a fourth factor $u_4 \in [0, 1)$. Combined with the innovativeness factor u_3 , we define a checklist uncertainty $u_B = u_4 \cdot u_3$, which is used in the Monte Carlo sampling to vary the achieved and maximum checklist scores. For the probabilistic modelling, normally distributed values $V' = N(V, u \cdot V)$ are sampled. The criteria are then recalculated and PROMETHEE is re-evaluated. Repeating this $n = 1000$ times yields a distribution of net flows that indicates how robust the ranking is with respect to parameter uncertainty.

Preference functions. In PROMETHEE, preference functions convert the difference between two alternatives on a given criterion C into a normalised preference value P . We select the Gaussian function (type VI) based on four selection criteria (see S2). This choice is particularly motivated by its smooth curve, which ensures stability under Monte Carlo simulation, provides graduated sensitivity to performance differences, and requires only one threshold parameter.

Weighting. Different use cases with different priorities require individual adjustment of the weighting. The evaluation of weighted criteria can prioritise any of the four dimensions, for example cost-effective cell production or high sustainability. PROMETHEE requires a weight for each criterion. There is no specific procedure for determining these values. We use scenario-based weight sets reflecting different user perspectives (see Section 3.6). Individual weightings $w \in (0, 1)$ are possible.

3.5. Evaluation method

The evaluation method integrates ten criteria across cost, throughput, quality, and sustainability into a single MCDA framework for battery production technologies. Each alternative is characterised by data-based criteria (C_1 - C_7), calculated from process parameters, and checklist-based criteria (C_8 - C_{10}), derived from weighted binary characteristics. PROMETHEE II is used with exclusion criteria and Gaussian preference functions. The approach aggregates this information into a net flow value ϕ^0 for each alternative, providing a complete ranking. Uncertainty in input parameters is incorporated via Monte Carlo simulation, and different user perspectives are represented through scenario-based weight sets. The overall evaluation process is summarised in Fig. 2.

3.6. Case study slitting

As an illustrative example, we apply the evaluation method to the electrode slitting process during electrode production (dividing mother coils into daughter coils). We compare a knife slitter and a laser slitter. Laser slitting can improve cutting quality, increase design flexibility, and is almost maintenance-free compared to knife slitting [80,81]. However, laser systems tend to be more expensive due to the laser hardware and consume more energy per electrode cut.

User scenarios and criteria weighting. The two process alternatives are evaluated using the ten evaluation criteria C . We define five user scenarios (balanced, cost-, throughput-, quality- and sustainability-focused; Table 5), each reflecting different priorities of potential users such as cell manufacturers. For this, we define criteria of high priority (C_{prio}), secondary priority (C_{sec}) and low importance (C_{low}). In all scenarios, criteria not directly related to the dimension in focus are categorised as C_{low} , indirectly related criteria as C_{sec} and directly related criteria as C_{prio} . We have set the relative weighting ratio at 1:2:4:

$$w_{low} = \frac{1}{1 \cdot |C_{low}| + 2 \cdot |C_{sec}| + 4 \cdot |C_{prio}|} \quad w_{sec} = 2 \cdot w_{low} \quad w_{prio} = 4 \cdot w_{low} \quad (1)$$

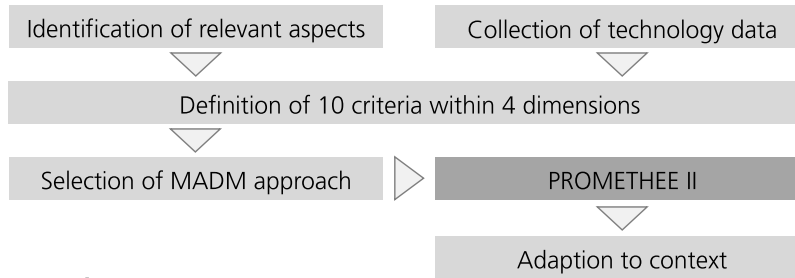
The balanced scenario is based on our own assessment of relevance. For the case study, we set the uncertainty factors to $u_1 = 0.05$, $u_2 = 1.2$, $u_3 = 1$, $u_4 = 0.1$ (where u_2 and u_3 are multipliers).

For the evaluation, the ten criteria were quantified using the formulas in S3. The corresponding parameters I and characteristics B are listed in S4. Investment costs for the knife system are based on a vendor offer, while other parameters (e.g. energy, throughput and scrap) are largely taken from the literature. Calculation results for both slitters are summarised in S5.

Fig. 3(a) shows the PROMETHEE net flow value ϕ^0 . The width of the violins represents the probability density of ϕ^0 from the simulation. The black horizontal lines mark the median. Fig. 3(b) shows the frequency with which each process alternative achieved the first rank in 1000 iterations of the Monte Carlo repetitions for all five scenarios.

Violins whose regions of highest density lie close together (e.g. in the throughput scenario) indicate that the ranking of the two slitting technologies is sensitive to parameter uncertainty. In such cases, reducing uncertainty (e.g. by improving the data quality) can increase

1. Method selection



2. Evaluation process

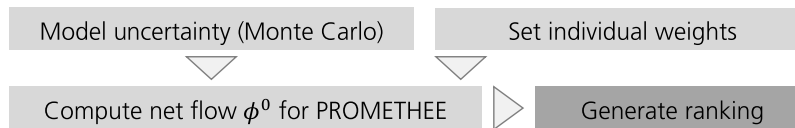


Fig. 2. Description of the methodological development leading to the technology evaluation.

Table 5

Weightings for evaluation criteria in different scenarios. C_{Prio} criteria are highlighted in bold.

Criterion	Balanced	Cost optimised	Throughput	Quality	Sustainability
Max. throughput	0.05	0.087	0.235	0.053	0.048
Scrap	0.05	0.087	0.118	0.211	0.095
Production output	0.15	0.087	0.235	0.053	0.095
Energy consumption	0.10	0.087	0.059	0.053	0.190
CO ₂ emissions	0.05	0.087	0.059	0.053	0.190
Investment costs	0.15	0.174	0.059	0.053	0.048
Operational costs	0.25	0.174	0.059	0.053	0.048
Manufacturing quality	0.10	0.087	0.059	0.211	0.048
Criticality & social	0.05	0.043	0.059	0.053	0.190
Fit & flexibility	0.05	0.087	0.059	0.211	0.048

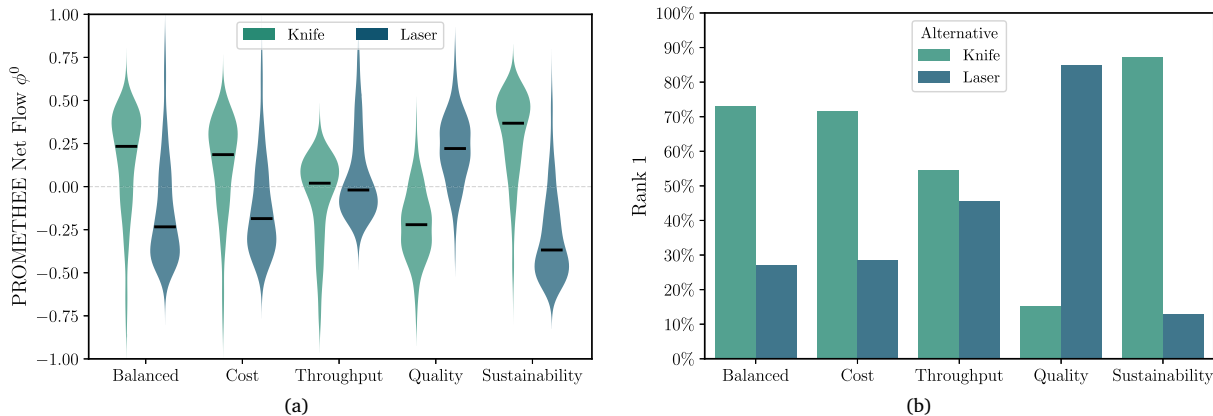


Fig. 3. PROMETHEE II net flow values (a) as well as ranks (b) for five different scenarios.

decision clarity. Separated violins or medians indicate a robust preference for one technology. This is also evident in the evaluation by rank. The more asymmetrical the bars, the more robust the result.

Depending on the scenario, knife or laser is preferred. The knife slitter dominates the balanced, cost, and sustainability scenario simulation (first rank in >70% of the repetitions). The reasons for this are, for example, lower investment costs and slightly lower energy consumption. Due to the lower scrap rate, the difference in the throughput scenario is smaller. In the quality scenario, laser slitting is clearly preferred (85%), driven by lower scrap and higher cutting flexibility.

Rank-reversal analysis. We use a rank-reversal (tipping point) analysis to determine the parameter value at which the PROMETHEE II ranking

between two technologies changes, i.e. where the difference between their median net flow values becomes zero ($\Delta\phi^0 = 0$). For this purpose, we focus on an example based on the balanced scenario, as it considers all four dimensions simultaneously. We vary the plant purchase cost of the laser slitter, because its higher investment cost is one of the main reasons for its poorer performance in the evaluation assessment compared to knife slitting.

We scale the plant purchase cost of the laser slitter by a factor k relative to its original value and vary this factor using a bisection (bracketing) approach on the interval $k \in [0.1, 10]$. For each iteration, Monte Carlo simulations are performed and the net flow difference between laser and knife is evaluated. In Fig. 4, the green line shows the median net flow, the shaded area the interquartile range, and the dots

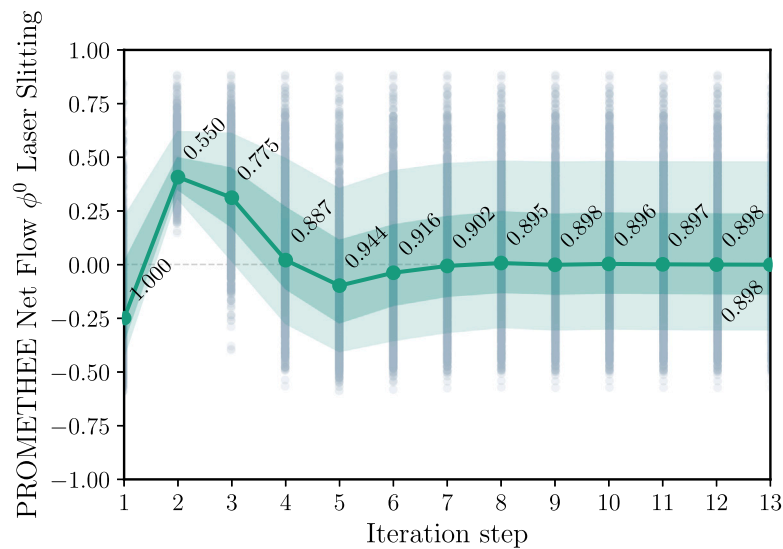


Fig. 4. Using the bracketing method to calculate the tipping point for the plant cost of the laser slitter outranking the knife slitter. The values in the diagram indicate the multiplier.

show the individual Monte Carlo samples. The numbers above each iteration indicate the factor k .

Starting from $k = 1$, the knife slitter dominates most of the samples (73%). The procedure converges to a threshold factor of $k = 0.898$, meaning that the laser slitter would need to be purchased at 89.8% of the assumed cost (i.e. a 10.2% cost reduction) to match the knife slitter in the balanced scenario. This means that, given its advantages, particularly in terms of quality, the laser slitter does not need to match the cost of the knife slitter.

4. Discussion

The case study demonstrates that the proposed multi-criteria evaluation framework can reasonably differentiate between competing production technologies and make trade-offs explicit. The method therefore does not provide an unambiguous ranking, but rather a structured way of comparing technology alternatives under explicitly stated preferences and assumptions. The values of the input parameters for the data-based criteria and the characteristics of the checklist-based criteria should be understood as illustrative and not as definitive recommendations. They provide a general framework that users can adapt and refine based on their own assumptions, data and practical experience.

The probabilistic modelling using Monte Carlo simulations and the visualisation using violin plots highlight where the method supports robust decisions and where input uncertainty dominates. Scenarios with clearly separated distributions and shifted medians (e.g. quality-oriented) indicate robust preferences. Even with parameter uncertainty, the probability of a ranking reversal in case of incorrect assumptions is low. In contrast, the strongly overlapping violin plots in the throughput scenario reveal a very unstable ranking between knife and laser. In this case, it is not possible to say unequivocally which technology alternative is preferable.

The evaluation approach presented in this work focuses on production processes at its core. Product aspects are considered indirectly (e.g. via mass loading of electrodes). Material or design changes must therefore first be translated into their effects on the production process. As a result, product and process characteristics can be taken into account.

Application potential of our method. A systematic technology evaluation is particularly important for new, innovative processes. Here, individual alternatives often offer advantages in some evaluation dimensions

while showing disadvantages in others compared to state-of-the-art technology.

Table 6 summarises innovative process technologies currently under investigation along the process chain of electrode production. The literature typically assigns quantitative or qualitative pros and cons to these technologies without providing a holistic comparison.

A prominent example is dry coating. It can reduce energy use and thus improve cost and sustainability. At the same time, there are challenges in upscaling and thus achieving the necessary throughputs to this date [111,112]. Over time, individual parameters (such as line speed) may change as the technology matures.

Lessons from the case study. The case study shows that the method can be used to relate these advantages and disadvantages to each other within a common analytical framework. The tipping point analysis (e.g. a required cost reduction of around 10% for the laser in the balanced scenario) translates these abstract trade-offs into concrete targets for technology development and procurement negotiations.

Data availability and method application. Finally, the quality of the technology assessment strongly depends on the quality of the underlying data. Considerable effort is required to compile consistent input values from manufacturer specifications, scattered literature and expert judgements. For some criteria (e.g. C_8 - C_{10}), there is little quantitative machine-level data. Additionally, available values often refer to nominal conditions or assumptions rather than measured operating data.

5. Conclusion and outlook

We presented a modelling approach for the evaluation of battery production technologies. Based on a literature review, we defined evaluation criteria that allow the battery process to be analysed in a holistic manner.

Using a preselection of MADM methods and the guidelines according to Guitouni and Martel [30], we identified PROMETHEE II as the most appropriate method and adapted it to the specific requirements of battery manufacturing. The method can handle different priority settings across different evaluation dimensions through flexible scenario-based weightings. By revealing the advantages and disadvantages of alternative process technologies, the multi-criteria evaluation approach provides decision support and a tool for sensitivity and tipping-point analyses, particularly for innovative processing technologies where data are scarce and uncertainty is high.

Table 6
Overview of process innovations and affected evaluation dimensions for electrode production.

Process step	Technology approach	Advantageous dimensions	Disadvantageous dimensions	Source
Cross-process	Dry coating	Cost, Sustainability	Quality, Throughput	[42,47,52,82–87]
Additional processes	Electrode structuring	Quality	Cost, Throughput	[52,88,89]
	Pre lithiation	Quality	Cost	[90–95]
Mixing	Continuous mixing	Throughput	Quality	[47,52,96–100]
Drying	Alternative drying (e.g. laser, microwave, infrared)	Cost, Sustainability	Quality	[42,52,101–108]
Vacuum Drying	Roll-to-roll vacuum drying	Throughput	Quality	[109,110]
	Cell baking	Cost	Quality	[110]

CRedit authorship contribution statement

Tim Wicke: Writing – review & editing, Writing – original draft, Visualization, Validation, Methodology, Investigation, Data curation, Conceptualization. **Christoph Neef:** Writing – review & editing, Supervision, Conceptualization. **Jens Tübke:** Writing – review & editing, Supervision, Conceptualization.

Declaration of generative AI and AI-assisted technologies in the manuscript preparation process

During the preparation of this work the authors used FHGenie (Fraunhofer internal AI platform providing access to common large language models) as well as Claude (Anthropic) to obtain suggestions for wording and structure and to improve the language and readability of the manuscript. After using this tool, the authors reviewed and edited the content as needed and take full responsibility for the content of the published article.

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Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Appendix A. Supplementary data

Supplementary material related to this article can be found online at <https://doi.org/10.1016/j.powera.2026.100211>.

Data availability

Data will be made available on request.

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