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Decision support based on cost and risk estimation to prioritize battery cell assembly technologies

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The need to overcome productivity bottlenecks in battery-production has initiated a rich diversity of assembly-processes that have reached different maturities today. These circumstances make it particularly challenging to envision future production chains, because any direct comparison of competing candidates is vulnerable to incompleteness, unfairness, and uncertainty. However imperfect the situation may be, organizations cannot skip the decision about which assembly technologies to prioritize in technology roadmaps. This motivates the proposed method, which is able to rank and prioritize candidates in the very volatile field of battery-assembly according to current maturity, cost estimated to reach the desired readiness and aspired performance.

assembly, cost, battery-production

1. Introduction and problem statement

The production of battery-cells accounts for more than one quarter of a battery-electric-vehicle's overall production costs [1]; furthermore, there is considerable potential for cost reduction through production technology innovations [2]. In this context, research suggest to emphasize production innovation efforts related to the assembly process of the electrode-separator-compound (ESC, located inside the battery), because it is one of the bottlenecks of the whole chain's productivity. This insight motivated a number of proposals for novel processes and equipment for ESC assembly over the recent years [3-10] and each of these has now reached different maturity. The aspired industrialization of such technologies and the decisions implied with such a roadmap always asks for the priorities to set on such candidates and for the sub-technologies to adopt therein. This should be based at least on estimates of the attainable performance, the effort expected, and the risks anticipated; this shall be the scope of this article and it is approached via a cost estimation method proposed in the following.

This article intents to contribute the following:

1. Method to quantify and compare the effort needed to industrialize technology candidates in the field of battery-assembly. Consider that candidates start from different technology readiness levels (TRL) and that the specific organization interested in elaborating these candidates starts with specific knowledge.
2. Practical demonstration how to implement the method and what information to obtain.

The article approaches the problem as follows: section 2 proposes a method for quantitative a-priori estimation of the cost and uncertainty which is needed to lift a given technology candidate from a current TRL to an aspired TRL. Section 3 illustrates the usage of this method in a research project context, in order to demonstrate the effectiveness and usefulness of the method. Section 4 concludes the findings and puts them into the wider context.

2. Proposed method, based on cost estimation readiness

2.1 Work related to technology decision support and cost estimation

Planning aspects related to battery production are mainly directed towards sustainability [11, 12], factory planning [13, 14], ramp-up [15], and/or process planning [16]. The only work which analyzes the industrialization efforts of pre-mature technologies in battery production refers to the assembly of all-solid state batteries [17], but this study must, because of the infancy of these technologies, remain on a coarse qualitative level. This deficiency and, additionally, the need to quantify risks to compare competing proposals motivates the proposal for a quantitative cost estimation approach.

Quantitative cost estimation methods are well-established in contexts where projects are very complex and a-priori lifecycle knowledge exists. Being faced continuously with these characteristics and the constant urge to adopt emerging technologies, aerospace engineering organisations have developed sophisticated methods [18-21]. The underlying principle is 1) to structure the overall budget problem into smaller budgets, 2) to give estimates about these costs, and 3) to add risk budget which corresponds to the TRL and the estimator's confidence. These methods provide quantitative cost estimates at the large scale, but when it comes to narrow scopes of detailed technology roadmapping, all what is stated is that experts' estimates should be used [22]. This paper intends to clarify this task by structuring a method for expert-based effort estimation. The result of this may be integrated into larger estimation schemes (and joined there with historical data at large scale), which is postponed to beyond the scope of this paper.

2.2 Proposed method for cost and risk estimation

Stage 1. "Analyse the value chain of battery-assembly": The value chain of battery-assembly is analyzed with regard to the throughput in the sub-processes from separation to formation for a given specific shape and hierarchical structure of the battery-cell to be assembled. Throughput-critical sub-processes are then identified and priorities are assigned.

Stage 2. "Create and conceptualize process candidates": Now, the scope is limited to the prioritized sub-process. The hierarchical structure of the battery-cell and the substructures therein are used to guide the search and identification of candidate assembly processes. The objective of this search is to identify manufacturing processes and joining processes for each of these substructures and their assembly (one must not forget to test whether joint processing of adjoint substructures is viable and/or recommendable). Not only own solutions can be developed, but also state of the art solutions can be adopted and, if necessary, improved. The solution search yields a set of process candidates. For each of these process candidates, assembly equipment is conceptualized. In view of the need to keep the scope within practical limitations, reasonable pre-rejection should take place.

Stage 3. "Evaluate and rank candidates' technical performance": The conceptualized process and equipment candidates are evaluated using a multi-criteria metrics or simulation-based approach [23]. This yields a comparison and creates a ranking. A set of criteria and performance indicators must be developed, which features at least the relative comparison of candidates. If feasible, absolute quantification should be preferred, but, in many engineering challenges, such quantification is not reasonable (because, for example, it may be physically meaningless, too cumbersome to obtain, or not even possible to compute).

Stage 4. „Evaluate and rank candidates' economical effort": For the reason that the process and equipment candidates may have different maturities (state-of-the-art solution vs. own solution to be developed), the economical effort for developing each candidate has to be estimated individually (from the perspective of the organization that intents to elaborate these candidates). For cost estimation a structured guidance is proposed, which intends a clustering approach to reveal systematically the appropriateness of examination methods regarding the cost-benefit-ratio, see Figure 1.

Initially the actual maturity of the process candidate has to be identified and classified according to NASAs' Technology Readiness Level (TRL) [24]. In case the process candidates are conceptualized already, the TRL must higher than level 2. Subsequently, the milestone to be passed in order to reach the next higher TRL (transition) has to be specified. Then, an expert team seeks and elaborates necessary engineering tasks and investigations to achieve this next TRL. The authors recommend starting with theoretical examination methods (e.g., analogy observations through assessment and comparison). If the engineering team is not equipped with sufficient knowledge to investigate the technical issue analytically, simulation-based or experimental examination approaches should be added. Particularly, if the flexibility in material and/or format is one of the requirements, it is highly recommended to go on with simulation-based methods to avoid the high effort in experimental investigation of the different formats and materials.

After identifying necessary tasks, the costs for each task have to be estimated by an expert team. It is suggested to cluster the costs according to the established value creation factors for production: *product, process, equipment, staff, and organization* [25]. The costs for the TRL-transition are totalled and the procedure of task identification and cost estimation is repeated until the desired TRL is reached.

When this cost estimation procedure has reached the desired TRL, detailed engineering a-priori knowledge of the expert team is incorporated to gain the most accurate estimation of the uncertainty according to NASAs' Cost Readiness Level (CRL) [18]. CRL ratings range from 4 with the highest uncertainty (±45%) to 8 with the lowest uncertainty (±5%). The CRL rating is based on the complexity of the task and the evaluation of the assessment competence of the expert team. Concerning these both factors, the CRL can be determined based on a given matrix (for further information, see [18]). As a final point, the estimated costs and uncertainties for each TRL-transition are cumulated.

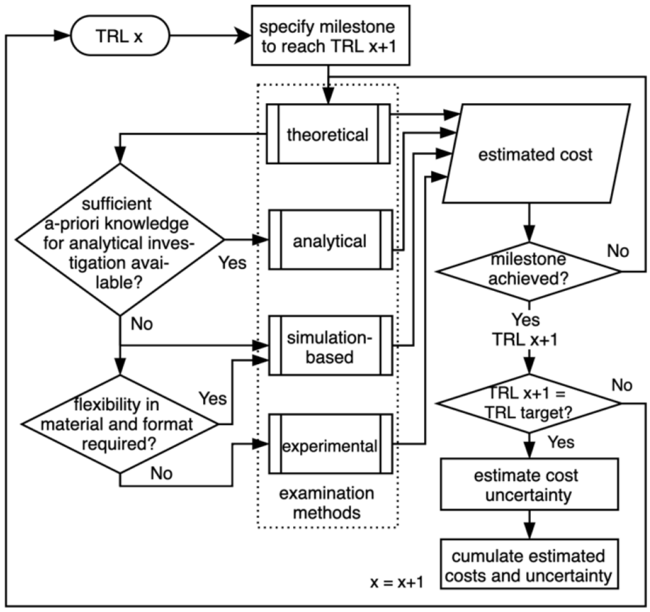

Figure 1: Structured guidance to reveal the examination methods depending on process candidates' maturity

Stage 5. "Draw portfolio diagram":
After the evaluation and ranking of the candidates' technical performance as well as estimated costs and uncertainties, these quantified values are drawn in a portfolio diagram in order to support the decision-making process.

2.3 Novelty of the proposed method

- provides a structured process flow and sub-processes for experts' estimates of effort, particularly for cases where prior knowledge is scarce.
- the sequential consideration of theoretical, analytical and experimental methods helps to anticipate appropriate examination methods.
- the categorization of costs with respect to the five value creation factors helps to attain completeness.
- the documentation of the process flow chart yields transparency, e.g. for review and update when other technologies emerge.
- the estimates reflect the minimum effort required to achieve the desired TRL transition. The risk budget added on top is determined according to [18], if no expert estimate can be anticipated.

3. Case study: cost estimation for battery ESC assembly

The following case study shall demonstrate the usefulness and practical information which can be gained from this quantitative cost estimation method. The task to be solved is to identify productivity bottlenecks in the battery ESC assembly and to elaborate a ranking for process candidates. For the purpose of demonstrating the accuracy of estimate for the most promising process candidate, the estimated and spent effort are compared.

3.1 Application of the cost estimation method

In the *first stage*, assembly process candidates for electrode-separator compounds (ESC) are reviewed. An attractive insight is that high-throughput assembly processes become more productive and reliable if they are fed by pre-products of reduced limpness. Such increased stiffness can be achieved through pre-joining of the electrode and the separator material prior to the stack assembly. It is noteworthy that this proposal is just one example out of many covered in the research of the authors;

however, for reason of limited space, the following elaboration will concentrate on this representative example.

In *stage 2*, several candidate joining processes for ESC-assembly were explored. After review, the 3 most promising candidates were conceptualized: 1-cold-glueing through jet dispensing, 2-cold-glueing through engraved roller, and 3-hot-laminating.

S*tage 3* comprises the evaluation and ranking of the joining process candidates' technical performance (Figure 2). The technical performance is represented by the throughput, the flexibility to intake different materials, and the flexibility to process different electrode formats. The gluing processes provide higher throughput through continuous process flow and heat independency. Due to the option to adjust the adhesive quickly, the material flexibility can be expected high for the gluing process. Engraved rollers for gluing need format-specific designs, which is why the format flexibility is considered lower. The laminating provides sufficient format flexibility but the thermal behavior of the materials processed limit the throughput. Moreover, the separator must contain fusible particles and tolerate high temperature gradients, thus the material flexibility is assumed lower.

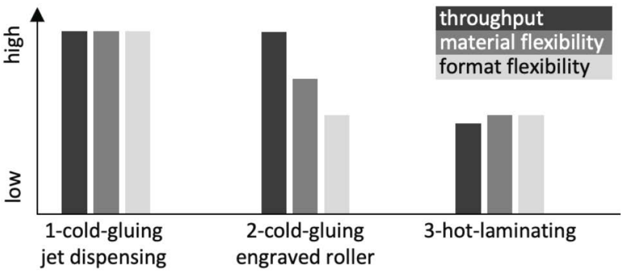

Figure 2: Joining process candidates' technical performance

In the 4th stage of the method, the joining process candidates are evaluated in terms of the economical effort necessary to raise the specific variants to the target-TRL. Note, these costs are estimated up to TRL 6 in this study, because a further increase to TRL 8-9 is largely dependent on knowledge transfer to suppliers [26] and considered beyond this study. The economical effort of each candidate is estimated by following the process flow in Figure 1. In order to illustrate this process, an example from the transition TRL 2→3 of candidate 1 is described in more detail here:

First, the milestone was defined which specifies that each individual component of the technology fulfills the requirements. Subsequently, it was analyzed which tasks and examination methods are necessary to ensure the suitability of the individual components, e.g. dispenser, adhesive, handling system. The theoretical examination method is always started with a review of known similar systems in order to be able to develop the individual components of the technology in a more systematic approach. Based on prior knowledge and the complexity, the team decided to carry out simple experimentation instead of analytical examinations. This was justified by the fact that the experimental implementation requires less effort at this low TRL. It was decided to simulate the forces the bond has to withstand during the assembly process, since theoretical analysis would be too simplified and an experimental setup would not be feasible here.

After all tasks have their individual examination methods (to reach the defined milestone for the TRL-transition) assigned, these are evaluated item-by-item in a spreadsheet with regard to their economical effort (product, process, equipment, staff and organization). The cumulated costs are then evaluated according to the CRL rating, resulting in an estimated value plus uncertainty for each task in the TRL-transition.

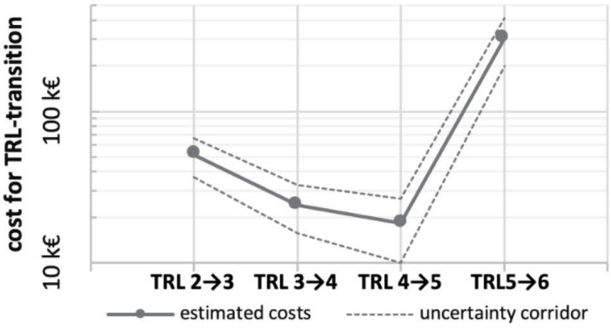

Figure 3: Cost estimation for candidate 1 – gluing with jet dispensing

Subsequently, all efforts required for the TRL-transition are summed up. This procedure is repeated iteratively for the subsequent TRL-transitions, until the desired TRL 6 is included in this calculation. The comparison of the cost of each TRL-transition provides valuable information, as depicted in Figure 3. In such a diagram, not only the a-priori estimate of the cost for each transition but also the cost corridor (defined by the quantified uncertainty) is included (dashed lines).

After the estimated TRL-transition costs for candidate 1 are determined, the competing variants are estimated by usage of the same scheme. Then the 5th stage of the method begins, where the TRL-transition costs per variant are accumulated and compared with the technical performance on Figure 4.

On the basis of this diagram, a specific organization can now evaluate which technology to prefer, depending on the technical performance and the expected development costs.

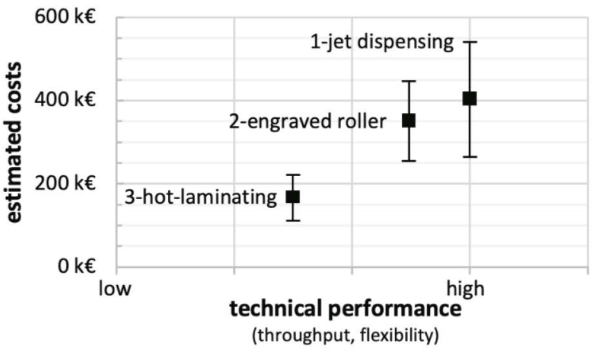

Figure 4: Portfolio diagram of process candidates

3.2 Lessons learned from the case study

In the project framework, candidate 1 was selected because of the expectation of best performance at reasonable budget. During the practical implementation, the real costs of each TRL-transition were logged (Figure 5, orange line). This reveals that the costs are within the estimated range. In summary, the estimate and real costs matches well. The person occupied with estimating should be aware that not every theoretical and practical examination method is always apparent in advance. Accordingly, if necessary, external experts should be involved in the evaluation to ensure that a strong a-priori knowledge is available for the estimation. A strong a-priori knowledge leads to the budget framework being estimated prudently and not being chosen too large through a lack of knowledge or too small through self-overestimation.

With the selection of a preferred variant, the estimate of the coming TRL-transitions can be updated after the completion of a TRL-transition in order to monitor the project, since the accuracy of the forecast rises with the increased knowledge. Consequently, budgets that were previously held back as a buffer for the next phase can be reallocated within the organization if necessary.

In the use cases surveyed beyond this article, it was repeatedly observed that the budgets along the TRL transitions form a characteristic bathtub curve: the initial costs are always high, due to the investments in the testing equipment. The curve then drops, since the correlations between electrochemical performance and the process step are largely investigated downstream, which primarily causes staff expenditure instead of investment. Subsequently, at TRL- transition 5→6, the cost rises again due to the development, manufacturing of a pilot scale prototype and the experimentation to qualify the respective process.

In the range of TRL 2 to 6, the largest cost in value creation are staff and equipment, in the following TRLs 7 to 9, a dominant cost position is to be expected in the value creation factor product, due to the many attempts at ramp-up and parameterization of the plant.

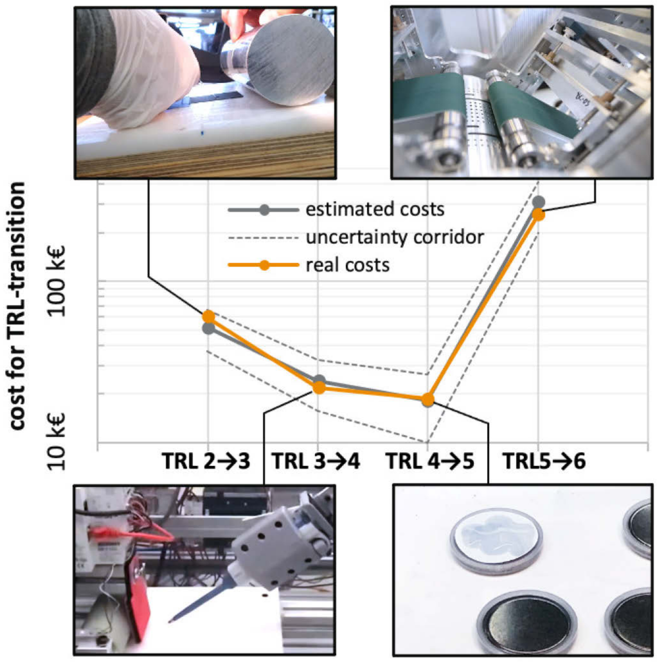

Figure 5: Estimated vs. real costs for process candidate 1. Illustrations show studies of individual TRL-transitions

4. Conclusions

The task of technology roadmapping for battery ESC assembly is adressed, which is a field of great volatility. In this field, existing methods are not informative enough for two reasons. First, most methods rely on historical experience, which is, unfortunately not yet enough available in battery assembly. Second, in such infant cases where historical data is sparse, such methods request expert estimates but not much specific structure is proposed. This paper structures a method to guide expert estimates in such situations where emerging technologies shall be brought to industrial maturity, which is particularly the case with battery ESC assembly.

The proposed method guides the expert estimates to bring a battery assembly technology from its current TRL to a desired level. It provides a framework to establish both, an estimate for the aspired technical performance as well as for the effort and risks. Particular emphasis is set on the transparent and structured sequence of questions and engineering methods to consider.

The method aggregates this data and yields a comparison of different configuration candidates in portfolio diagrams. From these diagrams, one may extract candidates from the regions of most interest. The method proposed goes beyond methods found in literature in the fact that there is more emphasis on the systematic revelation of appropriate engineering methods and on the quantification of the cost estimates and the risks anticipated.

The method has served to the authors successfully in multiple research projects. A representative example, "pre-joining of electrodes and separator prior to stacking", is used to demonstrate the method. This study shows both, the low effort to implement and the transparent decisions derived by this method.

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