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Building Blocks for an Automated Quality Assurance Concept in High Throughput Battery Cell Manufacturing

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Abstract

The increasing demand for sustainable energy raises the request for battery cells. Industry and research are faced with challenges like complex processes, complex machinery, and many intra-process interactions within the field of battery cell production. Major problems, such as low process stability and quality fluctuations, lead to high scrap rates. Result is a reduced sustainability in the production process. To address these challenges, the main content of this paper is a conceptual design of a virtual Quality Gate (QG) system, for quality assurance and quality prediction. The concept of virtual QG combines physical and digital elements. On the physical side actuators, sensors, and measurement technologies are included to provide the raw data. The digital side of virtual QG includes necessary elements for data acquisition, data processing, data analysis and information provision for the decision-making process in the real world. Focus of the presented approach is illustrating how to select the appropriate location of QG for quality decisions in conjunction with the derivation of necessary decisions, process information and evaluation of measurement technology that is needed.

Keywords: Automated Quality Assurance; Databased Decision Making; Sustainability; Quality Gates

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1. Introduction

Against the backdrop of climate change, the need for sustainable energy storages is becoming increasingly relevant. For this reason, a switch from conventional to electrical energy sources is currently taking place [1]. Therefore experts predict that the worldwide demand for battery cells will increase from around 200 GWh per year to over 2,000 GWh by 2030 [2]. This poses a major trend for industry and research as battery cell manufacturing still faces several key challenges within its processes. Battery cell production is characterized by complex process steps, complex machinery and many inter and intra process dependencies [3]. These factors cause problems such as quality fluctuations and low process stability. The result is that today's battery cell production is suffering from high rejection rates. [4]. This directly affects the sustainability of the value chain for new and environmentally friendly mobility concepts. Here, digitalization and the appropriate network in conjunction with the fourth industrial revolution provides great potential [5]. Virtual Quality Gates (QG) could be a possible enabler of automized quality assurance and have an impact to reduce scrap rates to create a more sustainable way of producing battery cells [6]. The focus of this paper is the implementation of virtual QG, by presenting a conceptual approach for the deployment of automated quality assurance in battery cell manufacturing.

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2. Battery Cell production

Lithium-ion technology based batteries have emerged as most common solution for a wide range of applications in the context of energy storage for mobility [7]. Three different cell formats (cylindric, pouch-shaped, prismatic) can be used [7]. The manufacturing process of battery cells can be divided into three main steps: electrode production, cell assembly and forming [8]. For electrode production many processes must be carried out under cleanroom conditions, as the intermediate product (cathode and anode) define the core properties of a cell such as capacity and impedance [8]. For producing cathode and anode, each electrode foil is coated with a prepared paste of active materials, then dried and calendared, cut into the required format, and dried again in vacuum [9,10]. Although the single assembly processes may differ between the cell types, the main process steps stay the same. The electrodes are placed into a housing, the cells are sealed and filled with electrolyte [7]. In the final stage of the process chain the assembled cells are formed, which means that the cells are charged to develop characteristic features. A functional test of the cells forms the final process step. [7]

3. Quality Assurance in Battery cell production

The quality problems of serial production of today's battery cell manufacturing lead to high scrap rates [11,12], producing a high material waste, which affects the sustainability of the industry. One solution is the early definition and detection of quality parameters and deviations (e.g. before the forming process) in order to reduce scrap [13]. Another weak spot is the partial lack of process knowledge and quality assurance concepts, especially in the ramp up phases for the production system [11]. Various data-based approaches and virtual QG concepts have been proposed in the literature as a solution to this problem. In the following, an overview will be given and a conceptual design for automated quality assurance will be shown.

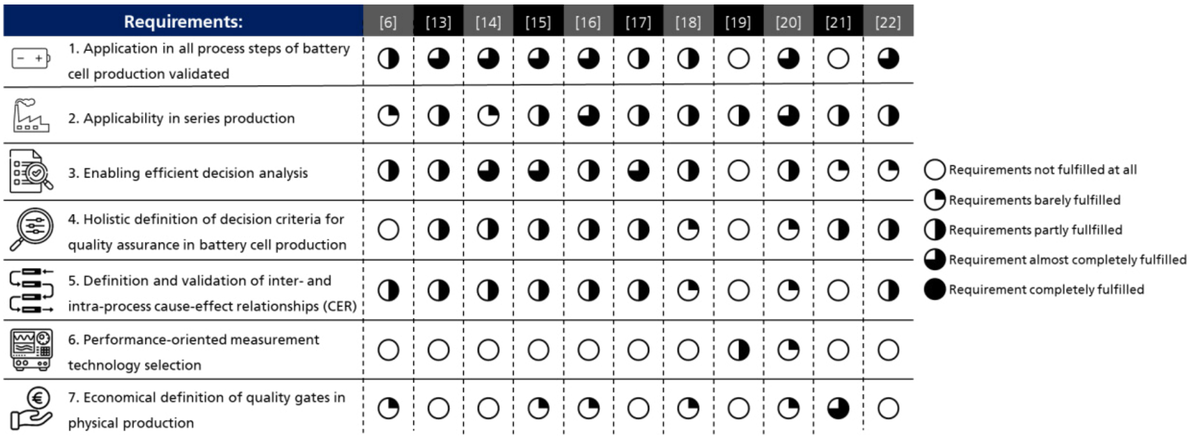
3.1. Literature Review for Quality Assurance Concepts in Battery Cell production

To review the existing approaches the requirements for implementing a quality assurance concept in battery cell manufacturing are defined as:

1. Application in all process steps of battery cell production validated
2. Applicability in series production
3. Enabling efficient decision analysis
4. Holistic definition of decision criteria for quality assurance in battery cell production
5. Dependency analysis across all process steps
6. Performance-oriented measurement technology selection
7. Economical definition of QG in physical production

The requirements and their respected fulfillment by an excerpt of the literature [6,13–22] are listed in figure 1. The fulfillment is rated in the range of "not fulfilled at all" to "completely fulfilled". As an example, the fulfillment grading is explained with the example of [13]. In this approach, the CRISP DM is applied to battery cell manufacturing for deriving interprocess relationships and key quality criteria from process data of battery cell manufacturing. Partly quality criteria and cause effect relationships (CER) are defined, but these are not fully complete and it is pointed out that their validation with further data is missing. This results in a partial fulfillment of requirement 4 and 5. Although the method is applied to a variety of process steps, it is pointed out that the applied models are not easily transferable to other processes or cell types. Thus, full compliance with the requirements 1. & 2. cannot be assessed. A selection of suitable measurement methods or economically reasonable QG is not considered in this paper but mentioned at in the outlook. Beyond that [13] offers a suitable possibility to perform decision analyses. [13] The findings of the literature review are supported by the work of [23], who pointed out that data-driven approaches to quality assurance in cell production are usually insufficient in their successful implementation and that a complete process monitoring along the entire process chain is missing [23]. In summary, the following research gap can be defined:

- The selection of economical suitable points for QG in physical production of battery cell manufacturing
- The definition of holistic decision criteria for quality assurance in battery cell manufacturing
- The selection of required measurement technology and interfaces in production
- The applicability for all cell types, processes, and series production



Requirements:	[6]	[13]	[14]	[15]	[16]	[17]	[18]	[19]	[20]	[21]	[22]
1. Application in all process steps of battery cell production validated	◑	◕	◕	◕	◕	◑	◑	○	◕	○	◕
2. Applicability in series production	◔	◑	◔	◑	◕	◑	◑	◑	◕	◑	◑
3. Enabling efficient decision analysis	◑	◑	◕	◕	◑	◕	◑	○	◑	◔	◔
4. Holistic definition of decision criteria for quality assurance in battery cell production	○	◑	◑	◑	◑	◑	◔	○	◔	◑	◑
5. Definition and validation of inter- and intra-process cause-effect relationships (CER)	◑	◑	◑	◑	◑	◑	◔	○	◔	○	◑
6. Performance-oriented measurement technology selection	○	○	○	○	○	○	○	◑	◔	○	○
7. Economical definition of quality gates in physical production	◔	○	○	◔	◔	○	◔	○	◔	◕	○

○ Requirements not fulfilled at all
◔ Requirements barely fulfilled
◑ Requirements partly fullfilled
◕ Requirement almost completely fulfilled
● Requirement completely fulfilled

Fig. 1: Literature review regarding quality assurance and data-based approaches in battery cell production [6,13-22].

3.2. Conceptual design for automated quality assurance in battery cell production

The following section introduces a concept for automated quality assurance, using QG. Traditional QG are physical decision points for quality assurance between two processes [21]. Relevant quality parameters are measured and compared with defined tolerances, resulting in a Pass/ Fail classification. The feedback of the Pass/ Fail decision into the production can be executed either mechanically or manually, depending on the degree of automation. If the qualitative requirements are not met, the intermediate product is physically rejected with the aid of actuators. Traditional QG consist of a solution for checking quality characteristics and an actuator system for physically separating the scrap. Within the process chain traditional QG only consider parameter of the immediate process, disregarding the overall quality of the battery cell. These traditional QG are usually used for quality description and classification. Options for quality planning or improvement are rarely implemented in traditional QG. [6,18]

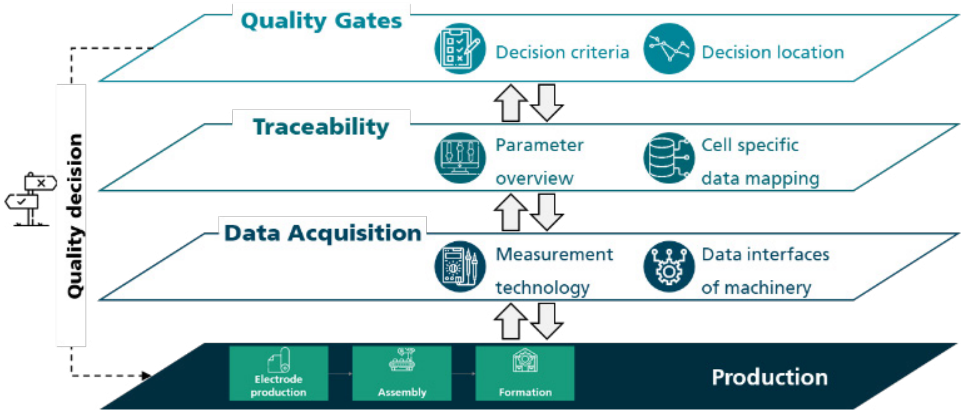


Fig. 2: Concept for automized quality assurance in battery cell production.

Beside this there is an existing approach of virtual QG in battery cell production. As an extension of traditional QG, they are created by using appropriate sensors and measurement technology to collect data, which is then transformed into decisions in the digital space [17,18]. The following concept defined in this paper builds upon the existing results of [17,18].

The components of the concept and their interaction are shown in Figure 2. It contains the elements production, data acquisition, traceability system, and QG. The production represents the physical entity of battery cell manufacturing. From this, the necessary data for quality decisions is extracted by means of suitable measurement technology and data interfaces of the machinery. This database is made traceable by a traceability system. It is important to trace the individual information cell by cell and, in addition, to be able to retrieve all the necessary information in a parameter overview. The QG can then be initialized based on this information. These contain the relevant decision criteria for quality decisions and define the location, where quality decisions must be fed back into production. After the conceptual structure has been presented, the methodical procedure for implementation is examined.

4. Building Blocks for implementing an automated quality assurance concept in battery cell production

To enable the implementation of the presented concept shown in Figure 2, the following targets need to be fulfilled:

- Optimization of economic and ecological factors through the appropriate selection of QG locations
- Generating process understanding through a methodological approach for process analysis regarding required decisions
- Holistic definition of decision criteria and process parameter correlation

Figure 3 shows the implementation of the concept, which is divided into the steps "Selection of Quality Gates", "Decision Analysis", "Process Analysis" (containing "Parameter analysis and definition" & "Parameter validation") and "Selection of suitable measurement technology". The presented concept and the approach for implementation are generic approaches which are specified for the use case of battery cell production. For example, during the selection of suitable QG locations, the parameters (Table 1) are adapted to battery cell production.

4.1. Selection of Quality Gates

The concept of automated Quality assurance shown in Fig. 2 accesses data collected across the entire process chain, but the actual separation of an intermediate product only takes place in specific locations in the process chain. This place is defined as a QG. Separation at every intermediate step would not be efficient and may even incur costs. Thus, the optimal QG for the appropriate separation in the process chain must be defined. This selection can be made under different priorities, for example, purely economic or purely ecological criteria, or a combination of both factors. The selection of QG is divided into 4 relevant steps (see Fig. 4). First, the available resources (costs, time, etc.) for implementing the QG are defined. Then the technical feasibility of the QG between or after a process step is analyzed. The goal is to identify possible locations to access and separate the qualitatively incorrect parts. Here, the machine configuration plays a crucial role. It is analyzed

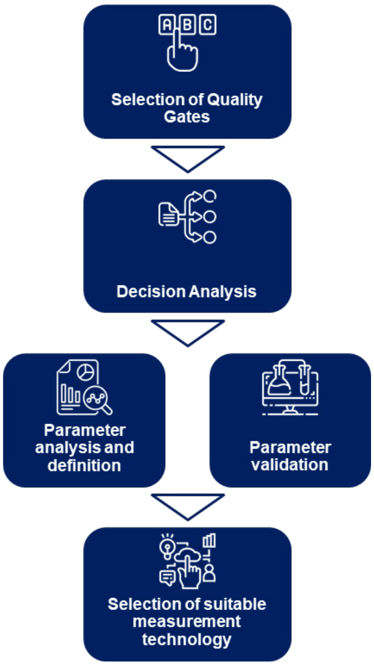


Fig. 3 - Approach for implementation of the conceptual design.

whether there is a feasible possibility, under constructive basic conditions, to extract the intermediate product (e.g coated substrate foil; after coating process) at the considered place from the production, without negative influencing of the process flow or the intermediate product. For this purpose, the processing task of the separation process as well as possible technical solution-profiles must be defined, compared, and evaluated between each process. Both results can be weighted regarding the previous chosen priorities to find the most suitable and technical feasible solution. [24]

Subsequently, points of the production are defined, where an ejection is mandatory, due to safety reasons. For the risk assessment regarding fire protection of the whole manufacturing system as well as the single process steps contained it is recommended by [25] to follow the DIN EN ISO 19353:2019 standard. In accordance with the method the single process steps get assessed regarding their fire risk and hazards within the process step as well as their influence on later hazards due to mistakes. The risk within a process step is assessed in three different categories. First the usage of flammable materials as a benchmark for the extent of damage is evaluated. Then an evaluation regarding probability of an ignition resulting from a process step and the controllability and propagation are assessed. As a result, a risk level gets assigned to each process step. [25]

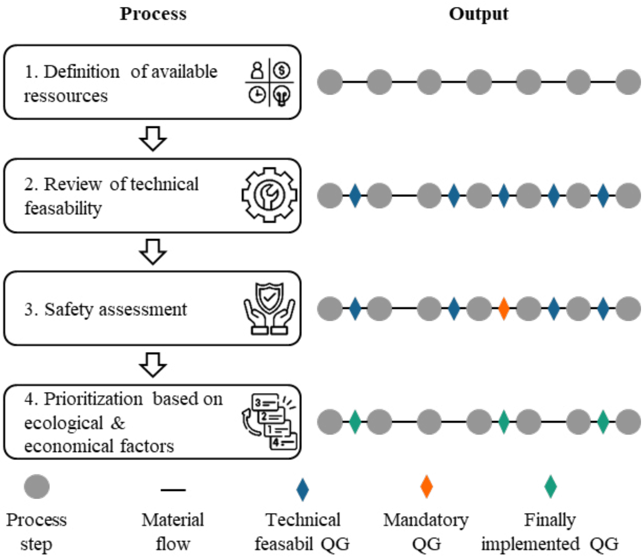


Fig. 4. Steps for the definition of QG locations.

After this third step, several optional QG remain in the production line of battery cell manufacturing, that are not mandatory for implementation due to safety-critical factors but technically feasible. For the final step the technically feasible QG are prioritized due to economic and ecological factors. For this purpose, an evaluation is made of how high the impact of the QG is on the following key performance indicators (KPI):

- Cell quality
- Time reduction
- Resource efficiency
- investment costs
- idle capacity costs
- operating costs

The parameters must be divided into different measured parameters. Table 1 shows an extract of examples for the KPI and measured parameters of the KPI groups "cell quality" and "time reduction". Based on the impact of the QG on the KPIs, a ranking of all QG can be performed. Considering the available resources, the highest ranked QG are implemented.

Table 1. Overview KPI extract (specified for battery cell manufacturing) for identification of QG locations.

KPI	*Parameters*	*Measured Parameters*
Cell quality	Capacity	Capacity (Ah)
Cell quality	Energy density	Composition of active materials (Wh/kg)
Cell quality	Energy density	Layer thickness (mm)
Cell quality	Power density	Composition of active materials (Wh/kg)
Cell quality	Power density	Layer thickness (mm)
Cell quality	Dimensions and structure	Height, width, length (mm)
Time reduction	Machine downtime	Machine downtime (s)
Time reduction	Set-up times	Set-up times (s)

4.2. Decision analysis

In the case of battery cell production, the intended use of the final battery cell, is decisive for the executed decision at a QG. The decision at each QG must answer the question, "What post-quality control activities are applicable to the intermediate product?" The subsequent action alternates based on the different boundary conditions. The following categories for QG are defined:

1. Intermediate product is OK: no adaptation of subsequent processes necessary
2. Intermediate product requires rework: adaptation of downstream process necessary
3. Intermediate product too badly damaged: intermediate product must be discharged directly

It should be noted that not all three categories are always feasible. In most of the defined QG (e.g. safety-critical ones), only the first two categories exist, since any damage to the component can have fatal consequences for further production. During decision analysis, also the following aspects must be discussed:

- Scenario analysis of possible defects
- Definition of the degree of automation of the quality decisions
- Definition of the way in which decisions are fed back into production

4.3. Process analysis (Parameter analysis and definition & Parameter validation)

To define a holistic overview on the needed quality criteria, an initial mapping and analysis of the process chain and cross-process cause-effect relationships (CER) are performed. Four steps have to be performed for initial parameter analysis and definition, based on expert knowledge [3]:

1. Process definition
2. Parameter definition
3. Cause effect relations analysis
4. Data acquisition (for result validation)

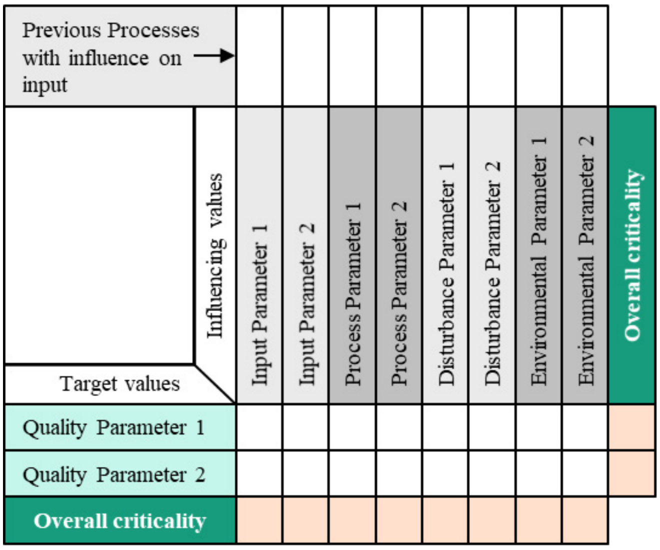
First the process chain in the production of battery cell manufacturing is defined. This includes a naming of each process, defining the correct process sequence and defining the intermediate products produced in the process. [3]

Subsequently the parameters that describe the different processes are identified. Therefore, the impact of every process on the overall product quality is carried out and the process parameters are divided into different categories [3]:

- input parameters
- process parameters
- environmental parameters
- disturbance parameters
- quality parameters

Each parameter is defined with a referencing target value and a maximum tolerance level. This information is crucial for setting up a traceability system to enable data acquisition.

In the third step CERs are carried out by evaluating intra- and inter-process dependencies. In this context, evaluation matrices (as shown in Fig. 5) are used, which are designed for the specific use case of battery cell production [3]. As in the matrix presented, the impact of the influencing values (input-, environmental-, disturbance- and process parameters) on the target values (quality parameters) is evaluated. Different criticality levels (very low, low, medium, high, or very high) describe the impact of influencing variables on the quality of the intermediate product. By documenting the pre-influence of the input variables, intra-process dependencies can be determined in addition to the inter-process dependencies. The respective criticalities also allow the determination of an overall criticality for each individual parameter. [3] In the final step, the derived criticality allows conclusions to be drawn about the frequency with which the respective parameter must be recorded and integrated in a traceability system.



Influencing values Target values	Input Parameter 1	Input Parameter 2	Process Parameter 1	Process Parameter 2	Disturbance Parameter 1	Disturbance Parameter 2	Environmental Parameter 1	Environmental Parameter 2	**Overall criticality**
Previous Processes with influence on input →									
Quality Parameter 1									
Quality Parameter 2									
Overall criticality									

Fig. 5. Matrix for CER identification [3].

For the validation of expert knowledge, a methodological approach must be applied. This methodological approach involves appropriate selection of experiments (e.g., by using the DoE method). In addition, different databased approaches (see Fig.1) are compared, with which the correlations in real data can be checked and either validated, discarded or new insights can be generated. The result is a complete overview of all decision criteria at the defined QG.

4.4. Selection of suitable measurement technology

The last step to implement the concept of automated quality assurance in battery cell production, aims to define suitable measuring methods, to enable the collection of all necessary data, for quality decisions. For this purpose, the generated decision criteria are analyzed about various points:

- The required information granularity
- The required frequency of the inspection
- The required measurement accuracy

On this basis, requirements for possible measurement methods can be derived. Subsequently, different measuring methods are compared with the requirements and a methodical procedure is used to select the most suitable measuring equipment. [19] shows an exemplary methodological approach of such a selection of measurement technologies for the use in tool design.

5. Review and Outlook

This paper shows the concrete need for automated quality assurance in the field of battery cell production. For this purpose, the introduction of an automated quality assurance concept, using virtual QG was recommended: It was shown how traditional QG systems are currently used, and in which forms they can be extended by databased approaches. For the deployment of an automated quality assurance concept in battery cell production, an approach for implementation of the concept is given. The focus of this paper lies on a methodological approach to prioritize locations of QG for data-based decisions during battery cell manufacturing. It was shown, what kind of decisions and actions are derived at the QG and how a holistic process analysis for defining critical process parameters and necessary measurements technology can be performed and validated. The presented approach shows a suitable concept, which must be validated in the subsequent stages in the use of series production. Overall, various trend topics can be addressed by the approach presented. For example, the holistic approach of virtual QG can have a valid impact on smart factories for battery cell productions in the future.

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