Energy Technology
Generation, Conversion, Storage, Distribution
www.entechnol.de

Tailored Digitalization in Electrode Manufacturing: The Backbone of Smart Lithium-Ion Battery Cell Production

Sajedeh Haghi, Armin Summer, Philipp Bauerschmidt, and Rüdiger Daub*

Following the introduction of Industry 4.0 and the development of information technologies, manufacturing companies have been undergoing a profound transformation. This transformation envisions the realization of the smart factory as a fully connected, flexible production system regulated by data. Digitalization and collection of the critical parameters are the vital prerequisites for this vision. Electrode manufacturing is regarded as the core phase in the battery cell production, having most of the properties determining the electrochemical performance of the battery cell established in this phase. There are a high number of parameters involved in electrode manufacturing. The digitalization of these parameters is associated with a considerable amount of effort and costs. Introducing a tailored digitalization concept provides the first step toward smart battery cell production. The tailored digitalization concept is based on the importance of the parameters from the quality management perspective and their complexity with regard to digitalization. The prioritization of parameters enables a successive quality-oriented digitalization strategy. The concept is built on a two-step literature-based and expert-based approach. The results include a comprehensive list of parameters and their prioritization for digitalization and integration in a tracking and tracing concept.

1. Introduction

The environmental regulations on CO_2 emissions have been a critical driver for the automotive industry's transformation over the last few years. The rechargeable battery cell is considered the main hurdle in this transformation. There are still specific challenges that need to be addressed for a market breakthrough of battery technology in the automotive industry.[1,2] A significant challenge is the battery cell costs that need to be reduced to have a cost-neutral product compared to conventional vehicles.[3] After the material costs, cost-efficient manufacturing is the second key factor, accounting for a significant portion of battery cell final costs. An analysis conducted by Boston Consulting Group suggests an approximate cost reduction of 20% that can be realized through the implementation of smart factory concepts in battery production.[4] A smart factory is characterized by providing context-aware support to the users and machines in accomplishing their tasks.[5] It enables the real-time collection, distribution, and access of manufacturing relevant information on products and processes.

Due to the high number of process steps with manifold interdependencies and the high share of material costs, battery cell production is characterized as a complex process chain with a cost-intensive scrap rate. An in-depth understanding of the process steps, their interdependencies, and early-stage scrap detection along the process chain can significantly reduce the total scrap rate.[1] Electrode manufacturing is considered the core phase in battery cell production, as most of the properties influencing the electrochemical performance of the battery cell are established in this phase.[6] The electrode manufacturing processes include a high number of product and process parameters with strong interdependencies.[6]

A substantial contribution to the smart battery cell production vision is the realization of data-driven solutions in electrode manufacturing. A data-driven solution can support practitioners in gaining an in-depth understanding of the process chain as a whole, making event-driven decisions, and reducing production errors. Schuh et al. presented this vision as the concept of the "internet of production" for manufacturing companies,[7] consisting of three primary levels; raw data, smart data, and smart experts. Digitalization is an essential prerequisite for a smart factory. A comprehensive review of the existing definitions of digitalization is presented by Reis et al.[8] The following definition is adopted in this article; digitalization refers to enabling and improving processes by leveraging digital technologies and sensors. It aims to facilitate the creation of transparency and broader utilization of digitized data, turned into intelligence and actionable knowledge.[8] As the definition suggests, the first step toward exploiting the potential of data is identifying the parameters, followed by selecting sensor and digital technologies. Two main orthogonal research objectives are identified in this field: "(i) real-time data collection and monitoring of tightly integrated production processes to enable seamless low-latency analysis and performance and (ii) storing and processing of heterogeneous

S. Haghi, A. Summer, P. Bauerschmidt, R. Daub
Institute for Machine Tools and Industrial Management
Technical University of Munich
Boltzmannstr. 15, 85748 Garching, Germany
E-mail: sajedeh.haghi@iwb.tum.de

The ORCID identification number(s) for the author(s) of this article can be found under https://doi.org/10.1002/ente.202200657.

DOI: 10.1002/ente.202200657

production data to facilitate scalable data stream processing."[9] This article aims to address the first objective and provide guidelines for the digitalization of electrode manufacturing.

Along with digitalization, a traceability system is a complementary component for realizing the full potential of data-driven solutions and enabling in-depth and holistic analysis of the interdependencies along the process chain. According to ISO 9000:2015, traceability is a crucial element of quality control.[10] It is defined as the ability to review the product history throughout the manufacturing chain.[10] A traceability system allows precise data mapping, which is essential, especially in electrode manufacturing with continuous process steps.[11,12] A tracking and tracing system provides the foundation for different use cases, from quality-oriented holistic analysis of the production processes to energy demand evaluation and optimization in production.[13] It should be noted that the realization of a traceability solution with a high degree of data granularity is associated with considerable costs, particularly in the continuous process steps with high-volume time series data. Therefore, the prioritization of parameters to be tracked on the electrode segment level is inevitable.

Turetskyy et al. presented a holistic concept for data acquisition and management in battery production based on the example of the Battery LabFactory Braunschweig (BLB).[14] Process or machine, energy demand, technical building services, intermediate product analytics, final product analytics, and operational data are defined as the six data sources in the proposed concept. A manual data acquisition strategy is suggested for the operational data, final product analytics, and partially intermediate product analytics. For the rest of the data sources, an automated data acquisition strategy is proposed. The parameters were identified through expert interviews of the technical and scientific staff of the facility. The article does not provide further details on prioritizing the parameters or selecting the data collection strategies for the data sources.

Ayerbe et al. reviewed the current status of digitalization in battery production and identified the challenges and the research gaps to be addressed.[15] The authors suggest a further investigation for using sensors and actuators in battery production. The topic of data acquisition and storage, interoperability of the data, usage of standard protocols, and interfaces are considered further challenges.[15]

Reynolds et al. evaluated possible metrology options for data collection in the electrode coating process.[16] The authors compared different measurement technologies based on their advantages and disadvantages for specific parameters such as coating thickness, mass loading, and defect detection. The review provides a broad overview of the parameters involved in the coating process and underlines the importance of a holistic analysis to develop a predictive understanding of the coating process. Similarly, Zhang et al. reviewed the key parameters in the drying process and the techniques that can be used to analyze this process step.[17]

This article aims to support the digitalization of electrode manufacturing of lithium-ion battery cells, addressing the research gap regarding the holistic, comprehensive approach for parameters and their relevance. The proposed approach enables the implementation of a successive quality-oriented cost-efficient digitalization strategy. The idea was introduced briefly as a tailored digitalization concept in the previous publication.[18] The tailored digitalization can be used as a stepping stone to implement data-driven solutions and acquire a comprehensive understanding of the process chain. A two-step, literature-based, and expert-based methodological approach is adopted to prioritize the parameters to be digitalized. The results include a literature-based list of parameters, their relevancy regarding quality management, and the complexity and effort involved in digitalizing these parameters. The prioritization of the parameters can be used to define the minimum requirement for data allocation in a quality-oriented tracking and tracing concept.

The remainder of this article is structured as follows. Section 2 outlines the tailored digitalization concept and its underlying scope and requirements. The methodologies used for the literature-based and expert-based prioritization of parameters are described in Sections 3 and 4, respectively. The final results are summarized in Section 5, while Section 6 delivers concluding remarks and an outlook on further research activities.

2. Scope and Requirements

Requirement elicitation is defined as a process of understanding a problem and its application domain. It is considered a fundamental and critical part of solution development. One of the primary definitions of requirement engineering states that "requirement definition is a careful assessment of the need that a system is to fulfill."[19] The definition has been initially introduced in the software engineering field. However, it can be adopted for the engineering design processes with a system seen as new solutions for products or procedures. Three attributes are considered in the requirements definition; the first one is the context analysis addressing why the system is needed, based on the current and foreseen conditions.[19] The second attribute is the functional specification, describing the features that satisfy the context. As the third attribute, the design constraints focus on how the system should be constructed and implemented.[19] Nuseibeh and Easterbook presented an overview of the techniques used to elicit requirements.[20] In this article, the traditional method based on the analysis of the existing literature is adopted. The formulation of the requirements follows the characteristics introduced by ISO 29 148.[21]

In the first step, the system's boundary conditions are established.[21] For this purpose, the manufacturing readiness level (MRL) is used. MRL is a systematic metric to assess the maturity of a production system and processes.[22] Similar to the technology readiness level, MRL is used to evaluate the maturity of a given system from a manufacturing perspective and identify the associated costs and risks. Production lines with different MRL require different levels of digitalization. The idea has been introduced with maturity models, assessing the digital readiness of manufacturing companies.[23] The MRL metric indicates the importance of demonstrating the capability to produce prototype components in a production-relevant environment. Keppeler et al. investigated this aspect for battery cell production in a comprehensive review, highlighting the importance of pilot lines.[24] With an MRL between 5 and 6, pilot production lines play a vital role as an intermediate step, enabling the results achieved at the laboratory scale to be transferred to industrial mass production.[24] The focus lies on the producibility and manufacturability assessment of key technologies and components. Pilot lines aim to evaluate the scalability and investigate the process parameters and their interactions.[24] With a reduced degree of automatization compared with industrial production, pilot lines are used to optimize quality control measurements from random sampling to 100% inspection.[24] Hence, the topics of digitalization and measurement technology take a substantial role in the pilot battery line production, which is considered here as the boundary condition.

Figure 1 presents an overview of the requirements defined for the tailored digitalization concept, divided into context analysis, functional specification, and design constraints. The developed concept should provide a guideline for digitalizing a pilot battery line and can be used for both greenfield and brownfield planning. The concept consists of universal solutions, not limited to a specific pilot line. A successive digitalization strategy would be possible through the proposed concept. The concept should follow a quality-driven strategy, considering the relevance of the parameters from the quality management perspective. A requirement to be considered in the development phase is transparency. A transparent and systematic approach ensures the replication and extension of the generated insights and results. With a detailed description of the methods used and the steps involved, the transferability of the developed concept for other similar use cases should be guaranteed. These requirements are used to evaluate the concept but are also considered in the course of solution development.

Besides the boundary condition and the requirements, the scope of the developed concept is to be defined. For this purpose, a reference technology chain for pilot-scale battery production is designated to increase transparency and provide specific yet universal solutions. The selected reference process consists of a multistage mixing process using a dissolver or planetary mixer, with material dosing considered as part of the process. Slurry preservation is an intermediate step before coating, based on the chosen mixing technology and batch production. The slot die technology, with doctor blade technology as optional, for a horizontal single-layer asynchronous coating with a coating speed up to 15 m min^{-1} is chosen for the coating process. The drying step is based on hot-air or infrared drying. A roll-to-roll machine with a line load of up to 1500 N mm^{-1} (width-dependent) was considered for the calendering process. The reference process chain was defined based on common technologies used in the lithium-ion battery production pilot lines. However, it should be noted that it is possible to include other technologies such as extrusion, comma-bar coating, or laser-based drying and adjust the results of the proposed concept accordingly.

Figure 2 outlines the approach and the methods adopted to develop a successive cost-efficient quality-oriented digitalization strategy. The first step involves a literature-based prioritization of the parameters based on interdependencies. The second step consists of a qualitative study based on expert knowledge.[25] While the first step reflects the importance of the parameter from the quality management perspective, the second step additionally incorporates the topic of complexity for digitalization. By including an expert-based paradigm, the approach benefits from complementarity, according to Greene and Caracelli.[26] Based on these two steps, the final prioritization of the parameters is conducted. The adopted methods and the results for each step are detailed in the following sections.

3. Literature-Based Prioritization of the Parameters Based on Their Interdependencies

The first step of the approach aims to prioritize the parameters based on the existing literature. The interdependencies described in the literature were used as input for a matrix-based modeling method to quantify the results. The matrix-based techniques are commonly used to facilitate the analysis of relations in complex systems.[27] In the following sections, the methodological approach and the results are described.

3.1. Methodological Approach

To manage the high complexity of electrode manufacturing and master the vast amount of information required to understand, design, and improve the process chain as a holistic system, the design structure matrix (DSM)[27] is adopted. DSM is represented as a square N × N matrix, mapping the interactions among the set of N system elements, identically labeled and ordered.[27] Compared with other modeling methods, the main advantage of a DSM is the graphical nature of the matrix display format, which provides a highly compact and intuitively readable representation of a system.[27]

The prevalent reading convention used in the DSM is input in row, feedback above diagonal (IR/FAD). However, the focus here is only on the interdependencies between the parameters, leading to their importance for monitoring and digitalization, not on

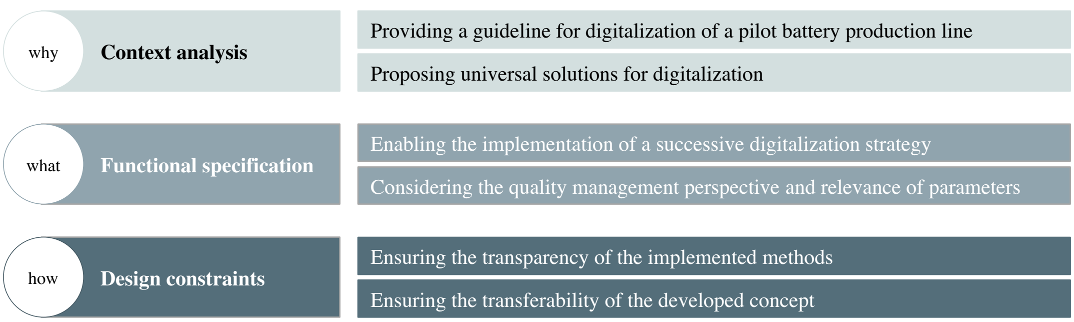
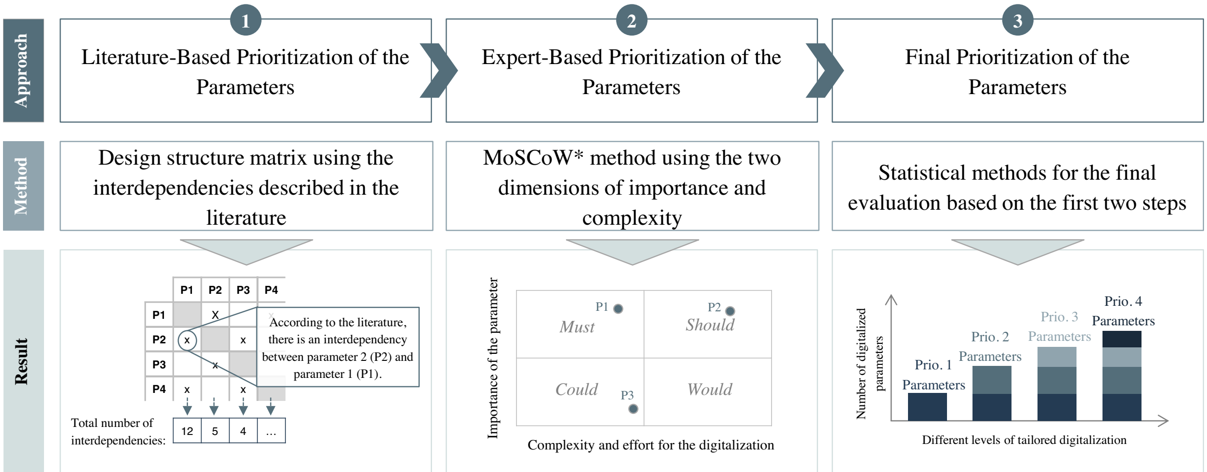


Figure 1. Requirements for the tailored digitalization concept.



* MoSCoW: a prioritization method, the acronym is derived from “Must, Should, Could, Would”

Figure 2. Overview of the adopted approach toward the tailored digitalization concept.

the cause and effect analysis. Hence a simplified version of the DSM is chosen, with interdependencies between two parameters shown simply with an “*x*” in the matrix, excluding the diagonal function. The result would be a symmetric matrix. Pimmler suggests a three-step approach for the development of the DSM: 1) decomposition of the system into elements, 2) documentation of the interactions between the system elements, and 3) clustering.[28] The results of these three phases are discussed in the following sections.

3.2. Parameters as Elements of the DSM

In the first step, the system is decomposed into its elements. For this purpose, electrode manufacturing is broken down into the process steps and the parameters involved in each process step.

To the best of the authors’ knowledge, the existing literature follows expert-based approaches within one organization to identify the parameters. This work adopted a literature-based approach to avoid subjectivity and include all the relevant parameters in electrode manufacturing. For this purpose, at least one article is included to reference each parameter. More than 50 publications were used as the basis for the identified parameters described in the following. The parameters for each process step are categorized into process parameters, product parameters (input), and product parameters (output). Process parameters include the controllable or measurable parameters that can be set or measured in the machine or by additional sensors. Furthermore, the parameters describing the production machine and the adopted tools are also considered in this category. The product parameters are divided into input and output parameters for each process step. As the name implies, the former represents the characteristics of the input material or semifinished products, while the latter describes the (semifinished) products after the process step.

The focus lies on the production research and hence the process steps. However, a short overview of the parameters related to the raw materials is also presented. It should be mentioned that some of the listed parameters might represent a redundancy in combination with other parameters, for example, drying rate and drying time in the drying process. However, the objective of this step is to include all the parameters that have been analyzed in the literature. Hence the redundancy aspect was disregarded.

3.2.1. Raw Materials and Production Environment

The electrochemical properties of the battery cell depend to a great extent on its materials, structure, and design. Hence, the topic of material development for better-performing battery cells has been a research objective in material and electrochemical science over the years. An excerpt of the material research publications is analyzed to provide an overview of the essential raw material properties of the electrodes. These include the current collector and the slurry components consisting of the active materials, binder, and conductive additives. In addition, the relevant parameters of the solvent for solvent-based electrode manufacturing are presented.

The first component of the slurry is the active material. A relevant parameter is the type of active material, such as lithium nickel cobalt manganese oxide (NMC), used for the electrode. An overview of potential materials with their performance characteristics and current limitations is presented in the study by Nitta et al.[29] The particle morphology of the raw materials is another critical parameter that can be modified by mixing and dispersing.[30,31] Particle properties play a significant role in the electrode performance; these include particle size of the conductive agent (e.g., carbon black),[30,32] their distribution,[33,34] and particle shape.[34,35] Grain or crystallite size is another indicator of electrode performance.[35,36] The residual moisture and formation of surface impurity during ambient storage, especially for certain cathode materials, are identified as indicators for the deterioration of the electrochemical properties.[37,38] Material properties such as electrical conductivity and bulk density of the active material are additional critical material parameters for the mixing process.[35,39] Furthermore, the porosity of the active material, pore diameter distribution, tortuosity, modulus of elasticity (Young's modulus), Poisson's ratio, fracture strength, and friction coefficient are considered relevant material parameters.[14]

Following the active material, the binder is the next raw material playing a crucial role in determining the electrochemical performance of the lithium-ion battery. The binder interconnects the active material and the conductive additive and adheres the electrode slurry to the current collector, preventing electrode delamination during the battery cycling procedure.[40] In addition, binder affects the slurry's rheological properties and mechanical stability, which are highly important in the following coating process.[41] Comprehensive reviews are presented in the literature on aqueous-based binders.[40,42–45] The chemical stability of the binder is considered the paramount requirement for its application in the battery cell.[40,42] Other analyzed properties include the type of the material,[45] the length of the polymer chain,[40,43,44] molecular weight,[40,44] molar volume, density, polymerization degree, crystallinity, and functional groups.[42] Thermal stability, diffusivity, and expansion rate are the significant thermal properties considered for the binders, affecting the electrodes' electrochemical performance and stability.[42] The mechanical properties include tensile and compressive strength, elasticity, flexibility, hardness, and adhesion.[42] The electrical and ionic conductivity are also to be considered.[42]

While active materials serve as a reservoir for lithium, the conductive additives or agents are used to increase the electrical conductivity of the slurry.[46] Specific surface area and density should be considered for the material's electrical conductivity.[46] In addition, the particle size is an additional relevant material property.[46–49]

The solvent is the last component in solvent-based electrode manufacturing to obtain a viscous slurry. The solvent concentration impacts the uniformity and stability of the dispersion and, consequently, the processability of the slurry.[50,51] The most important properties to be considered for choosing the solvent are viscosity, evaporation rate and boiling point, the solubility of polymers, dispersion stability, surface tension, and flashpoint.[52] An overview of common solvents' chemical and physical properties for electrode slurry is presented in the study by Bryntesen.[53]

As the last component in electrode manufacturing, the main properties of the current collector are presented in the following section. The first aspect is the type of material. While aluminium (Al) and copper (Cu) foils have been used since the first commercial lithium-ion battery, recent studies focus on alternative materials and structures to enhance the current collectors' electrochemical stability and electrical conductivity for the next battery generation.[54,55] The electrochemical stability, electrical conductivity, density, and mechanical properties are identified as critical indicators for current collectors.[54] The significant mechanical properties include the modulus of elasticity,[56,57] Poisson's ratio,[56] tensile strength,[57] and elongation at break.[57] The surface topography,[57] surface roughness,[54,57] and surface tension[58] affecting the adhesion are additional parameters relevant for the current collector. Furthermore, geometrical properties such as thickness,[57] area weight,[57] and width[59] are considered relevant concerning the mechanical properties of the current collector.

Another aspect to be considered, independent of the individual process steps, is the production environment. Studies have shown that nickel-rich materials such as $LiNi_{0,8}Mn_{0,1}Co_{0,1}O_2$ (NMC 811) are sensitive to moisture and environmental conditions.[38,60–62] To be able to track the possible influence of the production environment on the quality of the produced electrodes, parameters such as the type of the production environment, including a clean room or dry room with a specific dew point, the temperature of the room, and atmospheric humidity and pressure should be taken into account.[63]

3.2.2. Mixing Process

The mixing process is a critical step in electrode manufacturing, having irrevocable impacts not only on the electrochemical performance of the battery cell but also on the subsequent process steps. The slurry as a suspension consists of various components differing in size, shape, and density.[51] Consequently, there are challenges regarding the slurry's stability, sedimentation of the large particles, and agglomeration of the small particles.[51] The slurry's processability, uniformity, and stability directly affect the coating process's performance.[64] Hence, various studies have been conducted over the years with the aim of improving these aspects.[65–67] In addition, studies have been conducted recently to analyze the possibility of water-based dispersion processing of cathodes.[68] Compared with *N*-Methyl-2-pyrrolidone (NMP) as the currently common solvent used for cathodes, aqueous processing is desirable from the environmental, operational, and economic perspectives.[69] Other challenging aspects of the process include the lack of inline characterization methods for the suspension and the requirement for reducing the mixing time without compromising the quality of the slurry.

The process parameters in the mixing process include the rotational speed of the agitator,[70,71] the circumferential velocity,[70–72] mixing time for suspension production,[39,70,73] mixing time for solid powders (dry mixing time),[70,74] cooling temperature of the container during dispersing,[75] applied pressure during dispersing,[75] degassing time,[70] and pressure during degassing.[76] The mixing sequence is identified as an additional aspect influencing the characteristics of the battery cell.[74,77,78] Schilde et al. analyzed the efficiency of a dispersing process using the specific energy input.[79] The specific energy can be characterized by the energy input needed for the product's mass or the suspension's volume. Depending on the mixing method,[79,80] the geometry of the agitator,[39,70] the filling level, and the size of the mixing container,[14,24] the amount of mechanical energy input to the mixture is different. The motor current can be used as a parameter to characterize the energy input. Wenzel et al. investigated the influence of motor current during dry mixing on the material properties.[31] Depending on the dispersing device, shear stress can be used as an indicator for the minimum reachable particle size.[79,81]

The parameters for the slurry component listed in Section 3.2.1 could be considered input parameters for the mixing process. However, it should be noted that most of the listed parameters reflect a microperspective, which is usually analyzed in the laboratory environment.[60] For a pilot-scale production, the most relevant aspect is the recipe of the slurry, including the type and amount of active material, binder, conductive additives, and solvent.[65] Ligneel et al. investigated the effect of solid content on the rheological properties of anode slurries.[82] Ouyang et al. analyzed the uniformity and stability of cathode slurry to find the most suitable solid content.[51] From the raw material parameters, particle size,[30,32] bulk density,[39,80,83] and degree of impurity of the components[83,84] are also considered. As described in Section 3.2.1, residual moisture is an essential factor for cathode's active material with high nickel content.[38,60]

Parameters such as the temperature of the mixed material during the process,[85] powder conductivity,[70] and resistance after powder mixing[39,70] are used to characterize the semifinished product. The bulk density is the ratio of the weight to the volume of the mixed powders and can be measured by volumetric-controlled weight analysis.[86] The produced slurry's quantity is specified volumetrically or gravimetrically by its weight.[16,60] The most critical parameters for the slurry as the final product of the mixing process are its homogeneity and flow properties.[87] The performance of the battery cell is not only influenced by the types of raw materials used in the slurry but also their structural distribution.[48] Homogeneity describes this aspect with the components' consistency in size and distribution over the entire batch.[48,80] Parameters such as particle size distribution[88,89] and homogenous distribution of conductive agents (most often carbon black)[90] are identified in the literature as indicators for the homogeneity of the slurry. The uniformity of conductive agent distribution around active particles affects the final electrochemical properties.[91,92] The flowability of the slurry is described by the dynamic viscosity as a function of the shear rate[65,93] and its shear-thinning behavior (yield point).[65,78] Bauer and Nötzel considered cohesive energy as a measure of elastic strength, representing the work needed to maintain the spatial particle distribution.[65] The stability of a slurry is characterized by agglomeration and sedimentation rate.[64,94,95] The slurry's surface tension is particularly important for the subsequent coating process and the wettability of slurry onto current collectors.[64,96] Another parameter to characterize the slurry, which is consequently essential for the coating process when the slurry comes in contact with the aluminum collector, is the pH value.[97] Agitator's Reynolds number or Stokes number can be used as indicators to describe the flow behavior of the slurry.[87] **Figure 3** summarizes the parameters for the mixing process.

3.2.3. Coating Process

A key challenge in the coating process using the slot die technology is to find a suitable process window for a stable homogenous coating without any defects.[98,99] Since the coating process is closely interrelated with the drying process as a single unit roll-to-roll system, it should be adjusted and controlled, considering the requirements of the drying process. One primary requirement is the possibility of producing a thicker electrode for high-energy-density applications without adversely impacting the binder distribution in the electrode structure. For this purpose, different approaches such as multilayer coating have been investigated in the literature,[100,101] posing new challenges to the coating process.

As outlined in Section 2, slurry preservation is an intermediate step between the batch mixing and coating process. The storage condition plays a vital role in slurry processing, especially for NMP-based slurries.[48] To avoid slurry's sedimentation and aging effects, the produced slurry should either be directly processed in the coating step or be stirred during the storage.[48] The relevant parameters are the storage time,[48] container size,[98] and the material quantity to specify the filling degree of the container.[98] The last two parameters are relevant in case of stirring storage conditions. In addition, the slurry temperature before the coating process is relevant as it affects its flow behavior.[85]

Besides the geometry of the die in the slot die coating, such as slot gap and lip length,[102] the coating speed and web tension are critical process parameters.[16] The slot die coating is based on volumetric dosing; hence, the volume flow is another crucial process parameter, determining the volume of slurry applied in the coating process.[16] The die pressure and the coating bead pressure gradient take a prominent role in the slot die coating and the quality of the wet film.[103] The doctor blade coating follows the

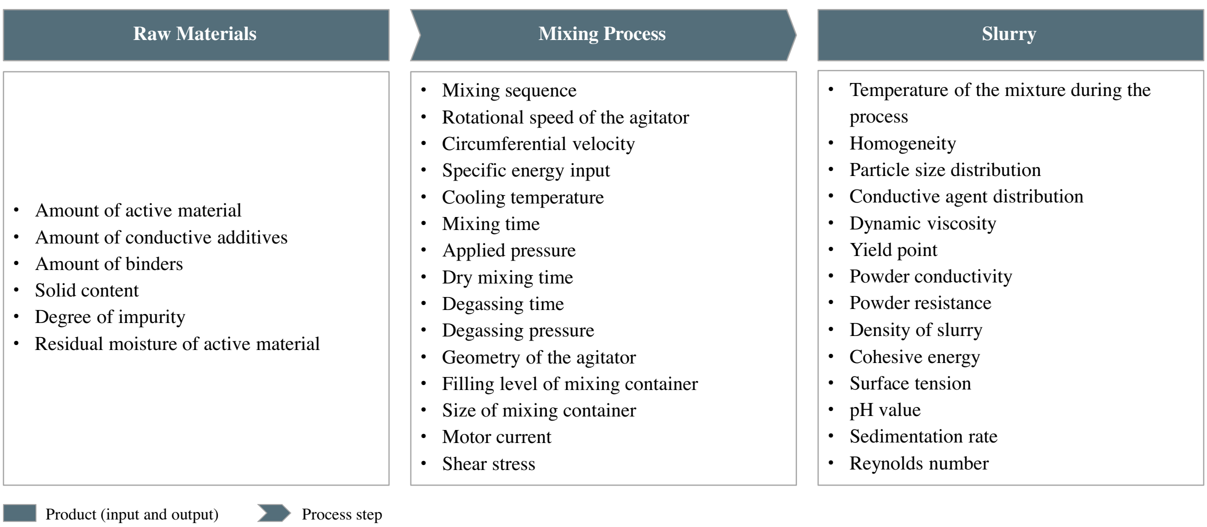


Figure 3. Overview of the product and process parameters in the mixing process (with an excerpt of raw material parameters).

mechanical dosing principle. Accordingly, the geometry defined by the coating gap determines the amount of slurry applied to the substrate.[16] However, the coating gap is also considered in the slot die coating as a quality indicator.[16,103,104] Current collector pretreatments such as flame treatment or electric discharge treatment (corona) can be used to increase the surface polarity and wettability.[58,105] The slurry's rheology combination with the coating shear rate and the shear stress influences the stability of the coating.[16] Other process parameters to consider in this process step are the angle between the tool and the web and the web alignment.[105] Some publications use the capillary number as a dimensionless quantity based on slurry viscosity, surface tension, and coating speed to describe the dynamic parameters in the coating windows.[81,106]

Due to the interlinked process chain, the output parameters from the mixing process serve as input parameters in the coating process. For a detailed description of the parameters, please refer to Section 3.2.2. Next to the slurry, the characteristics of the current collector are input parameters for coating. These are summarized in Section 3.2.1. A quality-critical undesirable phenomenon in the slot die coating is the formation of edge profiles. The edge profile describes the film elevations near the coating edges and at the beginning of each section during the intermittent coating process.[103] The wet film thickness, the coat weight (or the mass loading), and the quality of the wet film (absence of defects such as pinholes) are the major product properties in the coating process.[16] Another product parameter is the coating width,[48] which is also a decisive factor in the subsequent calendering process. A summary of the parameters, including an excerpt of the input parameters, is shown in **Figure 4**.

3.2.4. Drying Process

Drying is a complex process with simultaneous heat and mass transfer in three phases; solid, liquid, and gas.[64] The process parameters significantly influence the electrode's microstructure and its electrochemical and mechanical properties. Studies have shown that high temperature and drying rate can lead to an accumulation of binder on the electrode's surface, a condition often referred to as binder migration, which consequently has an adverse effect on the adhesion of the coating to the substrate.[71,73,107] Hence, a key challenge in the drying process is to attain the opposing objectives of reducing the drying time while producing a high-quality homogenous film. Jaiser et al. suggested a three-stage drying profile to address this conflict.[108]

Based on the drying rate, three distinct regions are suggested: a short region with an increasing drying rate, a more extended one with a constant drying rate, and a comparatively short one with a decreasing drying rate.[108] Considering the web speed[64,105] and the length of each drying section with the number of dryers,[64,70] the temperature profile, consisting of the temperature of each dryer,[73] is set accordingly. The drying process has also been investigated from the perspective of drying time and its effect on the adhesion of the electrodes.[73,94,109] The mass transfer coefficient of solvent[71,110] and the heat transfer coefficient[71,111] are used to understand the mass transport and heat transfer within the drying process. Additional parameters to consider are the web tension,[105] the surface temperature of the current collector,[109] and the surface temperature of the electrode.[109] In the case of convective drying, the velocity of the hot air, and for the infrared dryers, the emissivity of the dryer, is an additional process parameter.[112]

Similar to the coating process, the product input parameters in the drying process are the output parameters from the previous step. Among the output parameters, the coating adhesion is a crucial product parameter, influencing the electrochemical properties of the produced battery.[107,113] Besides the adhesion between the coating and the current collector after drying, the cohesion between the particles is another product parameter used to characterize the quality of the dried film.[109,114] Coating density, thickness, mass loading, and porosity are the common characteristics used to describe the final product in the drying process.[113] Next to porosity, tortuosity is adopted as a metric, describing the performance of the electrode.

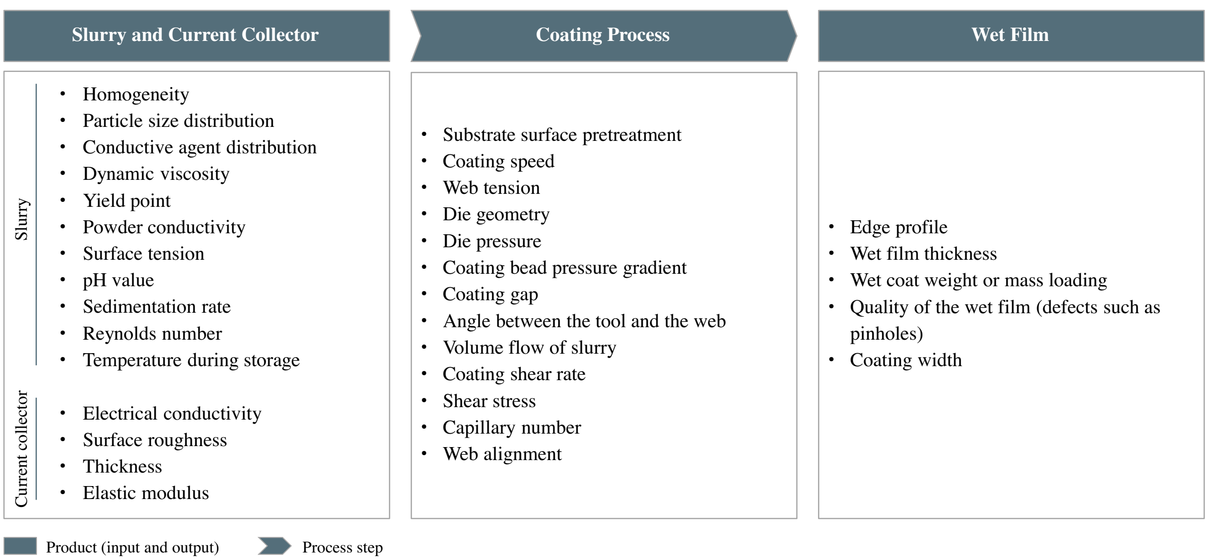


Figure 4. Overview of the product and process parameters in the coating process (with an excerpt of raw material parameters of the current collector).

Tortuosity is defined as the ratio of the average diffusion length across the electrode to the straight path length.[64] The morphology of the electrode is another product parameter considered in the drying process.[115] The moisture content or solvent concentration is an indicator adopted in the literature to characterize the process.[110] Mohanty et al. demonstrated the importance of homogeneity as a product parameter representing the uniform distribution of materials in the dried electrode for the performance of the battery cell.[99] The study included the effects of other electrode defects such as pinholes or agglomerates on battery performance.[99] The quality of the electrode surface can be used as a product parameter, representing these aspects.[16] **Figure 5** presents an overview of the parameters in the drying process.

3.2.5. Calendering Process

The main objective of the calendaring process is to improve the electrical conductivity and the volumetric energy density by applying mechanical forces. Given the targeted high energy density and the trend toward thin substrates and thick electrode layers, defect-free production is one of the significant challenges in this process step. A comprehensive overview of the calendering-induced defects and their consequences is presented by Günther et al.[116]

The main process parameters include line load,[117] the circumferential speed of the rolls,[118] the web speed,[119] and the temperature of the rolls.[120] The line load or the gap between the rolls[118] is used to achieve the compression rate.[118] Compaction resistance is another characteristic adopted to analyze the process.[119] The web tension[121] and precise web alignment are mentioned as additional aspects influencing the arising of possible defects in the process.[116] Parameters such as roll diameter[117] and concentricity accuracy of the rolls[122] are used to characterize the machine. A larger roll diameter leads to reduced shear stress[116] between the roll and the electrode surface, which is beneficial for the calendered electrode. Schreiner et al. studied the effect of horizontal and vertical displacement of the rolls as parameters of the machine behavior to model correlations between the machine and the electrode structure.[117]

Correspondingly, the product input parameters for the calendering process are the output parameters of the drying process. These can be found in Section 3.2.4. The product output parameters such as electrode thickness, porosity, and tortuosity are the essential parameters affecting the electrical and ionic conductivity of the electrode, thereby the battery's performance.[123] Next to the final porosity, homogeneity,[112] elasticity,[118] and the adhesion[117] of the electrode are ultimately determined after calendering. The plastic deformability of the electrode,[118] in combination with its elasticity[118] and its mechanical strength,[124] describes the mechanical behavior of the coated layer. The surface finish is another property influenced by the calendering process.[118,125] Product parameters such as coating width,[118] mass loading,[119] coating density,[117] and the pore size distribution[126] are additional aspects that are considered in setting up the process parameters. Similar to the drying process, the quality of the electrode concerning common electrode defects, such as the camber effect, is another product parameter to be considered in the calendering process.[116] Surface tension and shear stress are additional indicators of electrode defects after calendering.[116] The moisture content as an additional product parameter in combination with the coating density has been studied in the literature.[126] **Figure 6** summarizes the parameters in the calendering process. It should be mentioned that, based on the defined reference process, the slitting process is followed after calendering and is not considered here.

3.3. Interdependencies between the Parameters

In the second step, a systematic mapping study was conducted to develop the DSM. Kitchenham et al. explained the difference between systematic literature review and systematic mapping studies.[127,128] While systematic literature review is led by a particular research question that can be answered, for example, by empirical research, a mapping study evaluates a broader topic and classifies the primary research papers in that specific field.[128] The main steps involved in conducting a research synthesis are 1) formulating the problem, 2) searching the literature for primary studies, 3) screening for inclusion, 4) classifying the

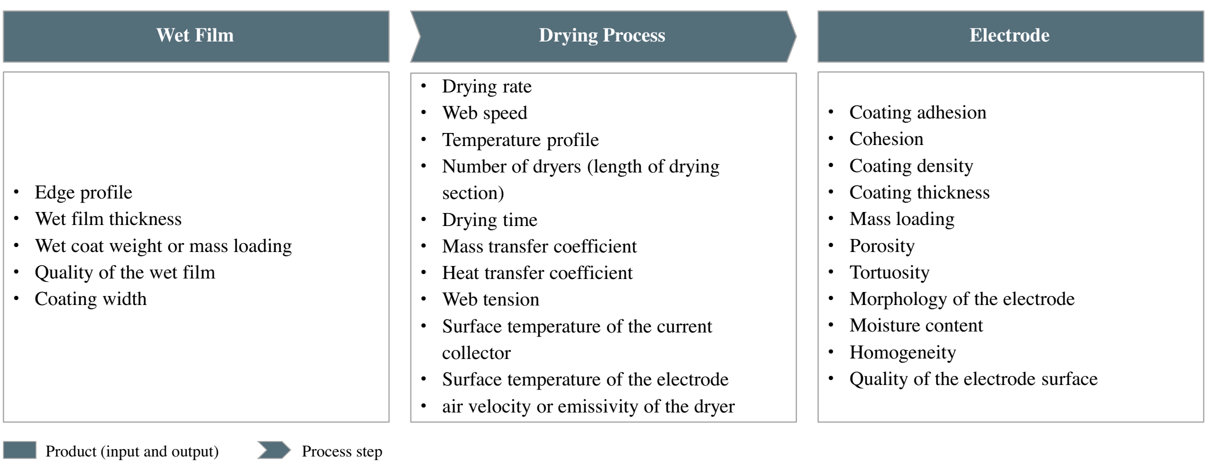


Figure 5. Overview of the product and process parameters in the drying process.

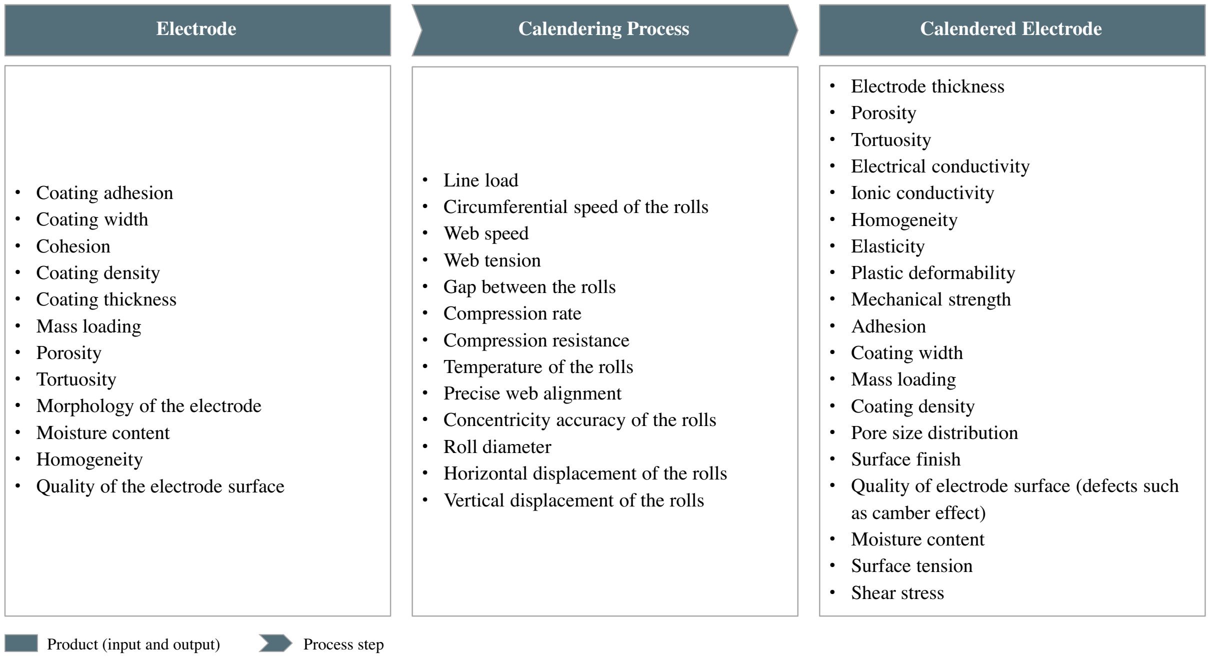


Figure 6. Overview of the product and process parameters in the calendering process (before slitting).

papers, 5) data extraction, and 6) aggregation.[128] It is important to note that the mentioned steps are not carried out linearly, as a vital trait of the review process is its iterative nature. Following the steps suggested by Kitchenham et al. and the search strategy displayed in **Table 1**, the *Web of Science* and *Scopus* database were searched, and 2,981 publications have been retrieved. The mapping study was conducted in the time interval between September and October 2021, concentrating on the papers published in the last 10 years. The primary target of the mapping study was the publications of production research; hence, the microscale studies in the fields of electrochemistry and material science were not included. In addition, only the open-access publications or journals with access possibility within the Technical University of Munich could be reviewed. By analyzing the abstracts of the search results, around 200 articles were found that were considered relevant. The identified publications were then classified based on the analyzed aspect, used material, and applied methods. **Figure 7** shows an excerpt of this analysis. An exhaustive overview of the analyzed literature can be found in Supporting Information.

Table 1. Search strategy for the development of the DSM.

Conceptualization	Operationalization
Keywords used in the query	(Batter* OR Electrode OR Anode OR Cathode OR Lithium-ion) AND (Product* OR Factory OR Manufact* OR Process OR mixing OR coating OR slot-die OR drying OR calendering) AND (Digital* OR Data-driven OR data mining OR machine learning OR Simulation OR Experiment* OR Analysis OR Quality OR interdepend* OR cause-and-effect)
Field of search	Article title, abstract, keywords
Timeline	2011–October 2021

The DSM was developed based on the identified literature, visualizing the interdependencies between the parameters. **Figure 8** illustrates an excerpt of the DSM for the process steps mixing and coating. The complete version of the DSM can be found in Supporting Information. The "*x*" in the matrix represents an interdependency between two parameters mentioned in the literature. As stated earlier, only the interrelations and not necessarily the cause-and-effect relationship were considered here. The results outline the importance of the parameters and the necessity for monitoring these parameters from the quality management perspective. In addition, the matrix can be used to identify the existing research gap in the literature and the need for further analysis of certain parameters and their interdependencies in the process chain.

3.4. Clustering the Results of the DSM

The last step proceeds with clustering the interactions between the parameters and the DSM results. For this purpose, a weighting factor representing the importance of each parameter within a process step was defined. The weighting factor for a parameter within a process step ($\mathrm{WF}_{\mathrm{P_i}}$) is calculated by Equation (1). For each "*x*" in the matrix, the variable (a_{ij}) is represented by the value one.

$$\mathrm{WF}_{\mathrm{P_i}} = \frac{\sum_{j=1}^{n} a_{ij}}{\sum_{j=1}^{n}\sum_{i=1}^{n} a_{ij}} \tag{1}$$

n: total number of parameters within a process step; i: row index of the matrix; j: column index of the matrix.

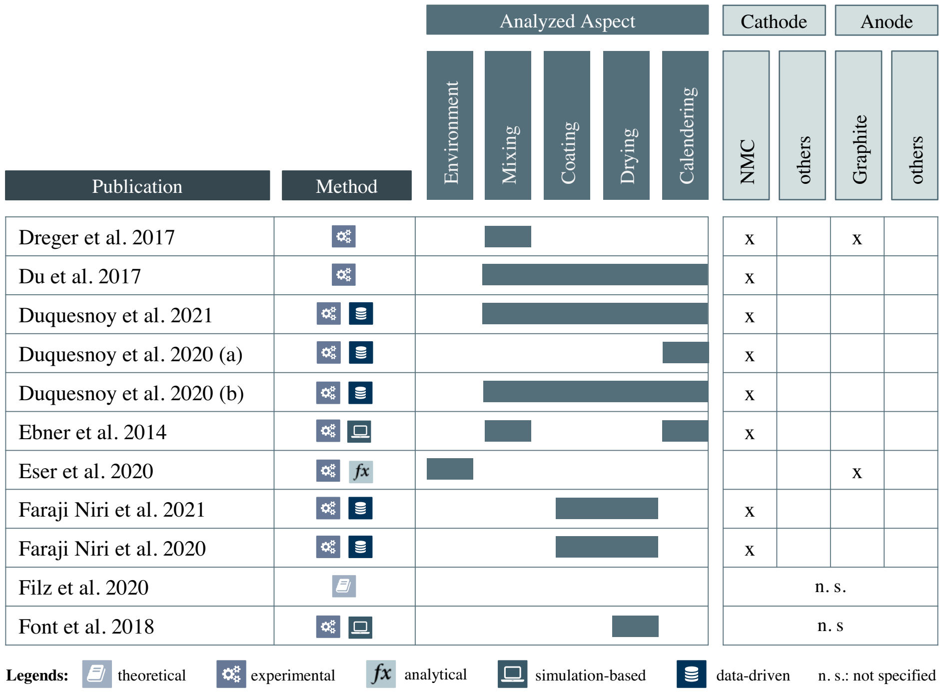


Figure 7. Excerpt of the overview of the analyzed publications with the adopted methods, analyzed aspects, and material systems.

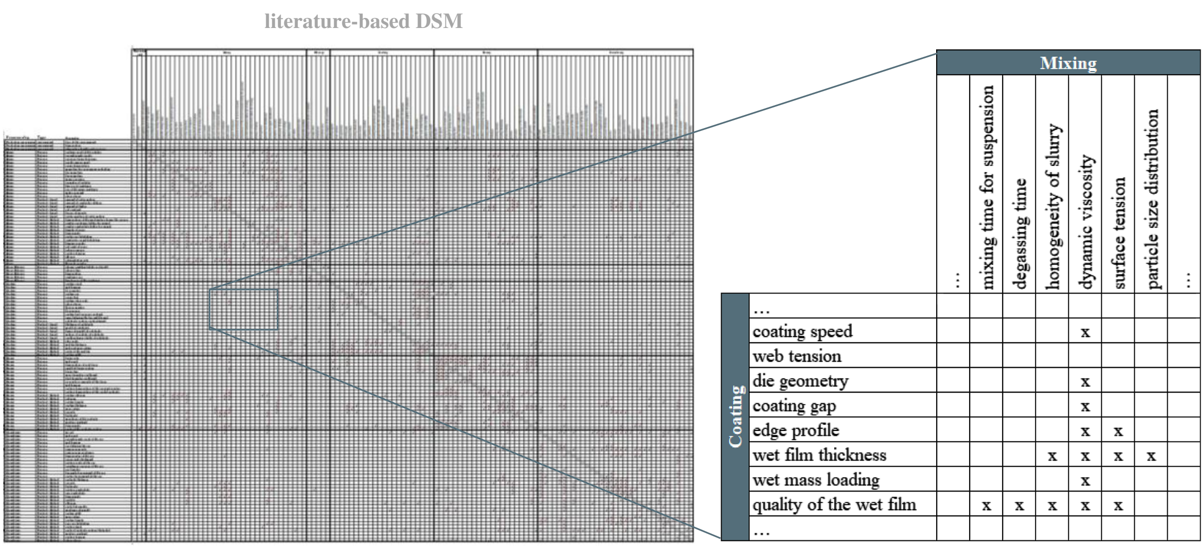


Figure 8. Overview of the developed DSM with an example shown for the interdependencies between a set of parameters in the coating and mixing process.

The parameters within one process step are divided into two prioritization categories using the calculated weighting factors. For the environment-related parameters reflecting a cross-process aspect, the weighting factors were calculated based on the interdependencies along the process chain, from mixing to calendering process. The process steps of coating and drying were considered one single unit due to their close interdependencies. As an initial step for the categorization, the outliers among the parameters were identified using the interquartile range. For the prioritization, the parameters with weighting factors higher than the average value within the process step were evaluated as a higher priority.

Table 2 presents an extract of the results for the coating and drying process. In total, 332 interdependencies were identified in the literature for these process steps as a single unit. Based on this total value and the number of interdependencies for each parameter, the weighting factor of each parameter is calculated (see Table 2). The highest weighting factor within these process

Table 2. Example of calculated weighting factors and prioritization of the parameters in the coating and drying process.

Process	Type of parameter	Parameter	Nr. of interdependencies	Weighting factor[a]	Priority[b]
Drying	Process	Drying rate	16	4.8%	1
Drying	Process	Web speed	13	3.9%	1
Drying	Product	Mass loading	16	5.1%	1
Drying	Product	Homogeneity of coating	10	3.0%	2
Drying	Product	Moisture content	9	2.7%	2

[a]Calculated according to Equation (1); [b]Evaluated between 1 and 2, with one as the higher priority.

steps is 6.9%, while the lowest is 0%. Hence parameters with weighting factors above the average value (3.4%) are considered high priority. The complete list of parameters with their weighting factors and literature-based prioritization is included in Supporting Information.

In total, 120 parameters were identified and classified into two prioritization categories. Aside from prioritizing parameters within each process step, the interdependencies for each parameter along the process chain of electrode manufacturing were quantified using the developed DSM. The matrix includes 1,204 bilateral interdependencies between the identified parameters. The minimum and maximum values were used to normalize the results. **Figure 9** shows the normalized values for the total number of interdependencies for each parameter along the process chain.

In addition, the locality of the interdependencies for each process step is depicted (Figure 9b). The parameters with the highest interdependencies along the process chain are the dynamic viscosity and the solid content of the slurry, the wet film thickness in the coating process, the line load, and the quality of the electrode surface for defects such as the camber effect in the calendering process. The results reflect the importance of each parameter from the quality management perspective along the electrode manufacturing and can be used as a basis to conduct cross-process analysis of the critical parameters in the process chain. The detailed list of normalized values for all the product and process parameters is included in the developed DSM and can be found in the Supporting Information.

4. Expert-Based Prioritization of the Parameters using the MoSCoW Method

For the second step of the approach, a problem-centered interview method was used, according to Witze and Reiter.[129] For this purpose, 12 workshops were held with experts from leading research institutes with years of experience in lithium-ion battery production. The workshops were conducted individually per process step. For each process step, four experts were interviewed. According to the definition presented by Bogner et al.,[130] experts are individuals with technical, empirical, and interpretative knowledge concerning their areas of expertise. They are able to use their interpretations to provide others with a concrete field of action as a guiding principle. **Figure 10** outlines the profile of the experts interviewed with years of experience in each process step. The process steps coating and drying were considered as one single unit.

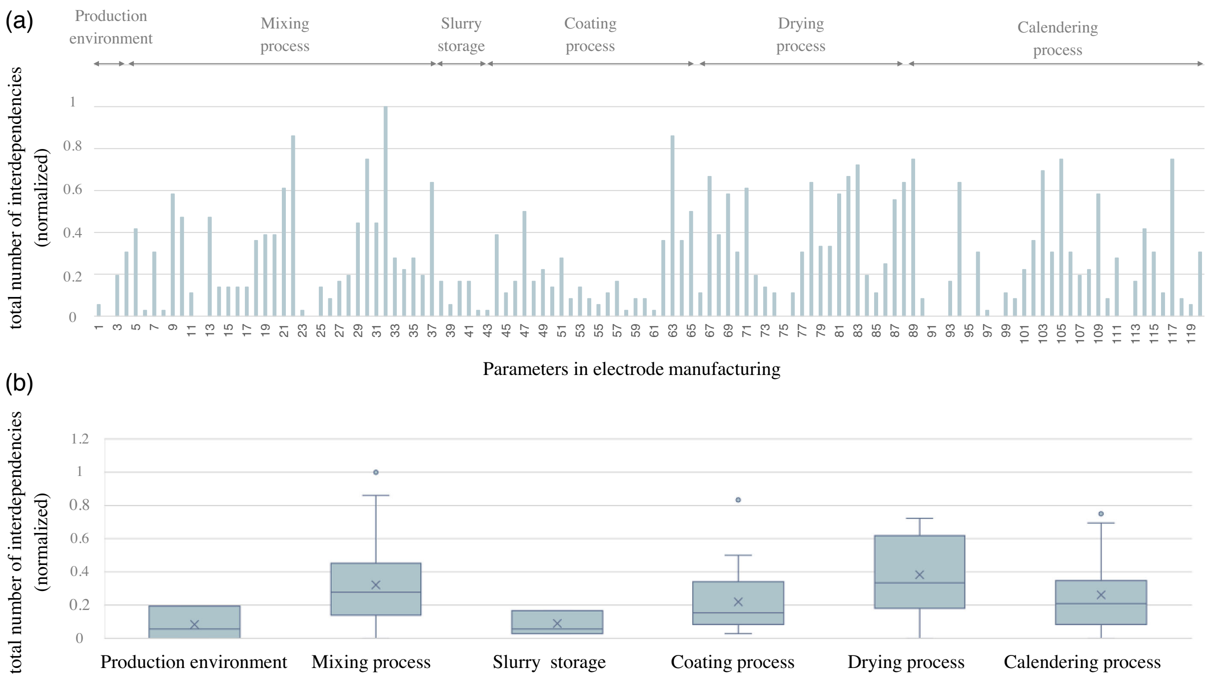


Figure 9. a) Normalized values representing the total number of interdependencies for each parameter along the electrode manufacturing process chain and b) box plot demonstrating the spread of the interdependencies for each process step.

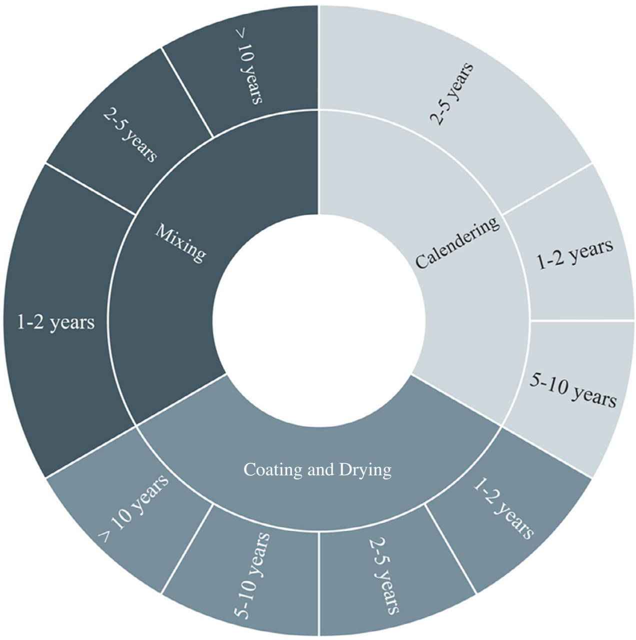


Figure 10. Profile of the experts interviewed with years of experience in each process step.

4.1. Preparation of the Expert Interviews

The structured expert interviews consisted of a dynamic questionnaire and a MoSCoW analysis. The dynamic questionnaire comprised queries about the experts' background and general questions regarding the most challenging aspects of the individual production process. The second part of the interview focused on prioritizing the parameters for digitalization. To this end, a short presentation was integrated into the interviews. The presentation included a brief introduction of the tailored digitalization concept, the prioritization method, and the reference process. The prioritization method was based on the MoSCoW analysis, originating from the dynamic systems development method.[131] MoSCoW analysis is a widespread prioritization method used in business analysis, agile project management, and software development. It was used to achieve common knowledge among the experts on the significance of requirements for digitalization. The term MoSCoW itself is derived from the first letter of the four prioritization categories (Must, Should, Could, Would). The results of a MoSCoW method are commonly represented on an ordinal scale. A matrix with two dimensions of importance and complexity was adopted as a complementary element to facilitate prioritizing the parameters and quantifying the results.

4.2. Conduction of the Expert Interviews

The interviews were held using online video and workshop tools (e.g., Microsoft teams, miro whiteboard). Following the dynamic questionnaire and the short presentation, the second part of the interview was conducted, consisting of three main sections, as shown in **Figure 11**.

The first section introduced the literature-based list of parameters, including process parameters and semifinished product parameters as input and output of the process step (see Section 3.2). This section allowed the experts to add additional parameters in case any were missing.

In the second section, the experts were asked to assign the parameters to the four prioritization categories according to the MoSCoW method. The importance of a parameter was evaluated based on its influence on the quality of the (semifinished) product or the subsequent process steps and their parameters. The horizontal axis represented the complexity involved in the digitalization of the parameter; this included the possibility for inline measurement, calibration efforts, accuracy, and costs. Both importance and complexity factors were evaluated on a scale between zero and five, with the former representing the lowest and the latter the highest level (see Figure 11). The two dimensions lead to the segmentation of the parameters into four categories. The "must" category represents the parameters that must be digitalized in the pilot line. The "should" category includes parameters with a high priority. The "could" category illustrates the desirable but not necessary parameters concerning digitalization. The "would" category contains parameters that do not essentially need to be digitalized but could be considered for the future, depending on the available budget and the application. The four categories represent the parameter's prioritization classes, with the "must" category as the highest priority and the "would" category as the lowest priority.

The third section was integrated into the expert workshops, as according to the evaluation, the "should" category includes

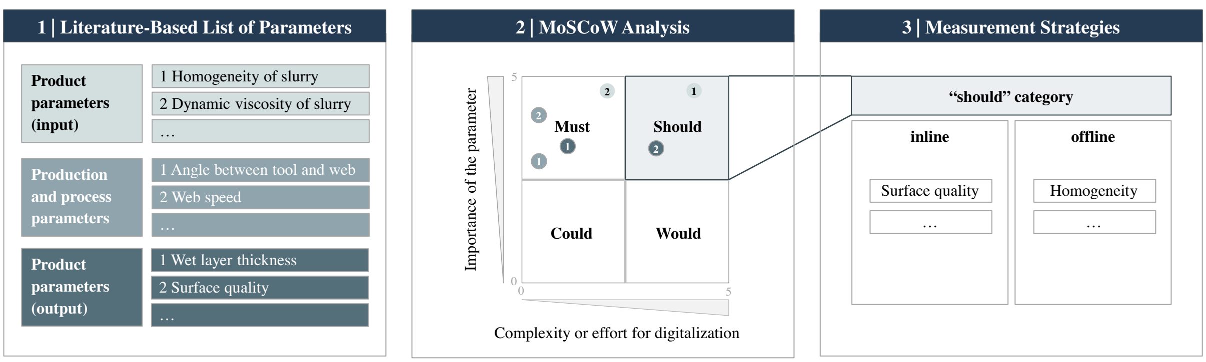


Figure 11. Methodological approach for the prioritization of the parameters in the expert workshops, illustrated based on the example of the coating and drying process.

parameters of high importance and concurrently, with great complexity regarding digitalization. A more refined segmentation regarding the measurement strategies (inline or offline) was included for this category. The determination of measurement strategies reflects the possibilities for inline measurement based on available solutions in the market and their necessity. The parameters assigned to an offline measurement strategy reveal the need to develop appropriate inline measurement solutions.

Following a tracking and tracing concept in battery production,[11] the experts for the continuous process steps (coating, drying, and calendering) were asked to highlight the relevant parameters for data allocation at the electrode segment level for the final battery cell. The result reflected a general consensus, with product parameters given priority over the process parameters for the precise data allocation.

4.3. Evaluation of the Expert Interviews

For a final assessment based on the four prioritization categories of the MoSCoW analysis, the expert's evaluations for the two factors (importance and complexity) were considered. For each parameter within a process step, two mean values were calculated. One was for the parameter's importance and another for its complexity. Based on these two mean values, a final allocation within the importance–complexity matrix was carried out. The option was given to experts to exclude parameters from the evaluation, depending on the confidence of the statement. This aspect has been additionally considered in the total assessment. Furthermore, each expert's final assignment of the parameters to the four prioritization categories was compared to the overall evaluation based on the mean values.

A set of product parameters were considered output parameters of a process step and input parameters for the subsequent process step. The average values based on the two sets of interviews for both process steps were calculated for these parameters, leading to a final prioritization in MoSCoW analysis. In addition, the parameters regarding the production environment were evaluated in each interview for each process step. For these parameters, the average value was calculated based on the results of the 12 interviews. **Table 3** presents an extract of the results of the interviews for the coating and drying process. As described in Section 4.2, the two factors were evaluated between zero and five,

Table 3. Example of the expert evaluations for parameters in the coating and drying process using the MoSCoW analysis.

Parameter	Importance[a)]	Complexity[a)]	MoSCoW Category	Priority[b)]
Drying rate	4.2	3	should	2
Web speed	4.7	0.2	must	1
Mass loading	4.3	1.5	must	1
Homogeneity of coating	2.9	4.7	should	2
Moisture content	3.4	3.9	should	2

[a)]Evaluated between 0 and 5, with 0 as the lowest level and 5 as the highest level; [b)]Evaluated between 1 and 4 according to the MoSCoW analysis, with 1 as the higher priority.

with five representing the highest level. Hence, parameters allocated to the "must" category are assessed with high importance (above 2.5) and manageable complexity (below 2.5). The "should" category includes parameters crucial to quality management and complex concerning digitalization (with a complexity factor above 2.5). The detailed outcomes of the interviews with the individual evaluation of each parameter can be found in Supporting Information.

5. Final Prioritization of the Parameters for Tailored Digitalization in Electrode Manufacturing

The results of the methods described in Section 3 and 4 are used for the final assessment of parameters. The DSM was adopted to prioritize the parameters regarding their relevance using the interdependencies described in the literature. Accordingly, the parameters were divided into two categories (see Table 2). In the MoSCoW analysis, the experts were asked to evaluate parameters based on the two factors of importance and complexity. The evaluations regarding the importance factor are comparable to the results of DSM. Hence, for the final assessment and prioritization of the parameters, an average value was calculated using the DSM and the importance factor from the MoSCoW analysis. In the first step, based on the scale chosen for the MoSCoW analysis and the average value (see Section 4.2), the results of the interviews were used to divide the parameters into two categories (priority 1, priority 2). Consequently, the results were compared to the outcome of the DSM, and an average value was calculated.

In some cases, discrepancies have been seen between the literature-based and the expert-based results. For example, according to the literature-based method, moisture content as a product parameter after the drying process was evaluated with a priority value of 2. According to the interviews, this parameter had an average importance factor of 3.4 (out of 5). As the evaluated value from the interviews is higher than the average (2.5), a priority value of 1 is assigned to this parameter. It should be noted that the results of the literature-based study are highly dependent on the availability and conventionality of measurement technologies in academia. There are currently near-infrared measurement systems available from €15.000 to €20.000 for the inline measurement of the moisture content. With further development of measurement technologies and cost-optimized solutions, this gap in the literature can be addressed in the future. Therefore, in the final evaluation of the importance factor, the results of interviews were used to prioritize the parameters in case of discrepancies.

The final prioritization of parameters into four categories according to the MoSCoW method was followed using the average value for the importance factors (based on DSM and interviews) and the evaluated complexity factor from the expert interviews. **Table 4** demonstrates the results based on a set of parameters in the coating and drying process. The detailed assessments for all parameters in the literature-based and expert-based methods are included in Supporting Information.

The results with the final prioritization of the parameters are summarized in **Table 5**. The importance factor is evaluated using the results of the DSM and the expert interviews, as described

Table 4. Example of the final evaluation of the parameters, with the importance of the parameters, assessed using the literature-based and expert-based results.

Parameter	Importance[a)]			Complexity (MoSCoW)[b)]	Final Priority[c)]
	DSM	Adjusted MoSCoW	Final evaluation		
Drying rate	1	1	1	3	2
Web speed	1	1	1	0.2	1
Mass loading	1	1	1	1.5	1
Homogeneity	2	1	1	3.7	2
Moisture content	2	1	1	3.9	2

[a)]Evaluated between 1 and 2 with 1 as the higher priority; [b)]Evaluated between 0 and 5, with 0 as the lowest level and 5 as the highest level; [c)]Evaluated between 1 and 4 according to the MoSCoW method, with 1 as the higher priority.

Table 5. Summary of the final results for the prioritization of the parameters in electrode manufacturing (based on the adjusted values for the importance and complexity factors).

Process Step	Parameter	Importance[a)]	Complexity[b)]	Priority[c)]
Production environment	type of the environment	1	1	1
	temperature	2	1	3
	atmospheric humidity and pressure	1	1	1
Mixing process	rotational speed of the agitator	1	1	1
	circumferential velocity	1	1	1
	pressure during dispersing	2	1	3
	specific energy input	1	1	1
	cooling temperature	2	1	3
	mixing time for suspension	1	1	1
	dry mixing time	1	1	1
	degassing time	1	1	1
	degassing pressure	2	1	3
	mixing sequence	1	1	1
	geometry of agitator	1	1	1
	filling level of container	1	1	1
	size of the mixing container	2	1	3
	motor current	2	1	3
	shear stress	1	2	2
	amount of active material	1	2	2
	amount of conductive additives	1	2	2

Table 5. Continued.

Process Step	Parameter	Importance[a)]	Complexity[b)]	Priority[c)]
	amount of binder	1	2	2
	solid content	1	1	1
	degree of impurity	1	2	2
	residual moisture of active material	1	1	1
	temperature of the mixed material	1	1	1
	powder resistance (after dry mixing)	2	2	4
	powder conductivity	2	2	4
	density of slurry	2	1	3
	homogeneity	1	2	2
	particle size distribution	1	2	2
	conductive agent distribution	1	2	2
	dynamic viscosity	1	1	1
	yield point of slurry	1	2	2
	cohesive energy	2	2	4
	surface tension	2	2	4
	pH value	2	1	3
	sedimentation rate	2	2	4
	Reynolds number	2	2	4
Slurry storage	storing condition (static or stirred)	2	1	3
	storage time	1	1	1
	temperature	2	1	3
	container size	2	1	3
	filling degree of the container	2	1	3
Coating process	coating speed	1	1	1
	web tension	1	1	1
	die geometry	1	1	1
	coating gap	1	2	2
	volume flow	1	1	1
	coating shear rate	1	2	2
	shear stress	1	2	2
	Capillary number	2	2	4

Table 5. Continued.

Process Step	Parameter	Importance[a)]	Complexity[b)]	Priority[c)]
	die pressure	1	1	1
	coating bead pressure gradient	1	1	1
	the angle between the tool and the web	1	1	1
	substrate surface pretreatment	2	1	3
	web alignment	1	1	1
	thickness of substrate	1	1	1
	weight of substrate	2	1	3
	tensile strength of substrate	2	2	4
	modulus of elasticity of substrate	2	2	4
	electrochemical stability of substrate	2	2	4
	edge profile	1	1	1
	wet film thickness	1	1	1
	wet coat mass loading	1	2	2
	quality of the wet film	1	2	2
	coating width	1	1	1
Drying process	drying rate	1	2	2
	web speed	1	1	1
	temperature profile	1	1	1
	length of drying section	1	1	1
	drying time	1	1	1
	mass transfer coefficient	1	2	2
	heat transfer coefficient	1	2	2
	air velocity or emissivity of the dryer	2	1	3
	web tension	2	1	3
	surface temperature of the current collector	1	2	2
	surface temperature of the coated electrode	1	1	1
	coating adhesion	1	2	2
	cohesion	1	2	2
	coating density	1	2	2

Table 5. Continued.

Process Step	Parameter	Importance[a)]	Complexity[b)]	Priority[c)]
	coating thickness	1	1	1
	mass loading	1	1	1
	porosity	1	2	2
	tortuosity	2	2	4
	morphology of the electrode	1	2	2
	moisture content	1	2	2
	homogeneity	1	2	2
	quality of the electrode surface	1	2	2
Calendering process	line load	1	1	1
	web speed	1	1	1
	circumferential speed of the rolls	2	1	3
	web tension	1	1	1
	gap between the rolls	1	1	1
	compression rate	1	2	2
	compression resistance	1	2	2
	temperature of the rolls	1	1	1
	precise web alignment	1	1	1
	concentricity accuracy of the rolls	1	2	2
	rolls' diameter	1	1	1
	horizontal displacement of the rolls	1	1	1
	vertical displacement of the rolls	1	1	1
	electrode thickness	1	1	1
	porosity	1	2	2
	tortuosity	1	2	2
	electrical conductivity	2	2	4
	ionic conductivity	2	2	4
	homogeneity	2	2	4
	elasticity	1	2	2
	adhesion	1	2	2
	plastic deformability	1	2	2

Table 5. Continued.

Process Step	Parameter	Importance[a)]	Complexity[b)]	Priority[c)]
	mechanical strength	1	2	2
	coating width	1	1	1
	mass loading	1	1	1
	coating density	2	2	4
	pore size distribution	1	2	2
	surface finish	2	1	3
	quality of electrode surface (defects)	1	2	2
	moisture content	2	2	4
	surface tension	1	2	2
	shear stress	1	2	2

[a)]Evaluated between 1 and 2. with one as the higher priority; [b)]Evaluated between 1 and 2, with 1 as the lowest level of complexity; [c)]Evaluated between 1 and 4 according to the MoSCoW method, with 1 as the higher priority.

Importance: highly important parameter, less important parameter.

Priority: must, should, could, would.

above. Accordingly, the results of the expert interviews for the assessment of the complexity factor were adjusted using the average value. Parameters evaluated with the value 1 represent a lower level of complexity for digitalization. A set of product parameters were considered output parameters of a process step and input parameters for the subsequent process step. These parameters are listed only once in Table 5, in the first associated process step. For the evaluation, however, both relevant process steps are considered (see Section 4.3).

The final results based on the combined evaluation methods are visualized in **Figure 12**. Among 120 identified parameters, 47 parameters were evaluated as the highest priority. The coating and drying process constitutes the largest share in this category with 19 parameters. The "should" category includes 39 parameters. The results indicate the lowest number of parameters for the "could" and "would" categories with 18 and 16 parameters, respectively.

The developed concept with the parameters evaluated as the top priority can be used as the minimum requirement for data allocation in a tracking and tracing system in battery production. One of the challenging aspects of implementing such systems is finding the appropriate data resolution level. The higher data granularity, with an increased number of parameters to be tracked on the electrode or battery cell level, the higher the related costs. Thus, the quality-oriented, cost-efficient prioritization concept contributes to finding the trade-off point in this matter. The data allocation strategy can be further specified, for example, both product and process parameters should be allocated to the electrode segments for the ramp-up phase. A tracking and tracing system allows the analysis of process parameters and the resulting product parameters with a high data granularity on the electrode segment level. Combined with data-driven solutions, this provides the possibility for a detailed analysis of the interdependencies, in-depth process understanding, derivation of lessons learnt, and long-term improvement of the ramp-up phase. After the ramp-up phase with the suitable process parameters identified, it is sufficient to assign the process parameters only to the batch level and the product parameters to the electrode segment level.

The developed concept can also be used as a benchmark for gap analysis and identification of the following digitalization measurements in a pilot production line. Additionally, the proposed prioritization can be used as an indicator for the frequency of data collection and storage strategies. The "should" category, representing parameters with high relevance and high complexity regarding digitalization, can be used to identify the need for further development of measurement technologies.

During the development of the proposed concept, the defined requirements and the scope of the solution were considered. The concept was based on both qualitative and quantitative research methods. For the qualitative methods, process specialists from different organizations were integrated to ensure the universality of the solution. Each approach and the adopted methods were described in detail to ensure transparency and transferability. The results are based on the defined reference process according

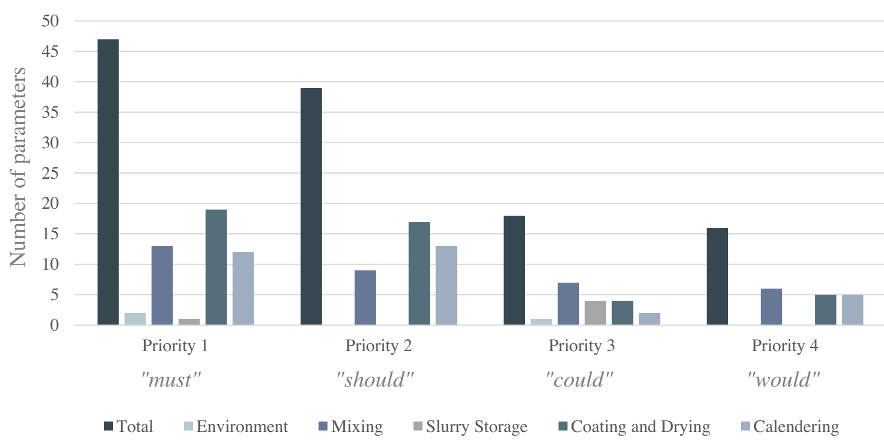


Figure 12. Final results for the prioritization of the parameters in electrode manufacturing using literature-based and expert-based methods.

to state of the art (see Section 2). With further technology development and introduction of new production routes such as dry coating, the result should be modified accordingly, as the set of parameters and their relevance differ from solvent-based electrode manufacturing. The same applies to measurement technologies. The "should" and "would" categories represent high effort and cost regarding digitalization. With further development of the sensor technologies, especially the inline measurement solutions, the evaluation of the complexity factor should be revised, which leads to modification of the final prioritization.

6. Summary and Outlook

This article has focused on providing a detailed guideline for implementing digitalization in electrode manufacturing. For this purpose, a tailored digitalization concept was developed, using a two-step literature-based and expert-based approach. Based on the proposed approach and defined reference process, the parameters were divided into four categories, using two dimensions of importance and complexity regarding digitalization. Parameters evaluated with high complexity regarding digitalization reflect the need for further development of sensor technologies. The concept can be used to assist both researchers and practitioners in implementing successive cost-efficient quality-oriented digitalization strategies and defining the minimum requirement for data allocation in a tracking and tracing system for continuous process steps. To the best of the authors' knowledge, this is the first time that an exhaustive literature-based list of parameters in electrode manufacturing and their relevance regarding quality management were presented. Additionally, the results of the literature mapping presented in Section 3 provide a solid starting point for the research community members interested in the topic of interdependencies in electrode manufacturing.

Future work will focus on exploring different measurement solutions in the digitalization of electrode manufacturing. Additionally, the final results can be verified using the Delphi method.[132] The developed DSM can be used as a guideline for developing data-driven solutions, analyzing the interdependencies in electrode manufacturing.

Supporting Information

Supporting Information is available from the Wiley Online Library or from the author.

Acknowledgements

This research work was conducted as part of the TrackBatt project (grant number: 03XP0310), funded by the German Federal Ministry of Education and Research, abbreviated BMBF. The authors gratefully acknowledge the financial support provided by BMBF. Additionally, the authors express their sincere gratitude to Dr. Philip Scharfer, Dr. Werner Bauer, Benjamin Bold, Marcel Dittmer, Alexander Schoo, Sören Scheffler, Patrick Schörwerth, Klaus Scherer, Thomas Römer, Josef Keilhofer, and David Schreiner for their time and valuable input during the interviews. The authors would also like to thank Fabian Konwitschny, Sebastian Kröger, and Celestine Singer for proofreading the manuscript.

Open Access funding enabled and organized by Projekt DEAL.

Conflict of Interest

The authors declare no conflict of interest.

Data Availability Statement

The data that support the findings of this study are openly available in Mendeley Data at https://doi.org/10.17632/6yy8wwfj3f.1, reference number 1017632.

Keywords

battery production, digitalization, electrode manufacturing, interdependencies, quality management, smart production, tracking and tracing

Received: June 23, 2022
Revised: July 20, 2022
Published online: August 2, 2022

[1] A. Kwade, W. Haselrieder, R. Leithoff, A. Modlinger, F. Dietrich, K. Droeder, *Nat Energy* **2018**, *3*, 290.
[2] Y. Liu, R. Zhang, J. Wang, Y. Wang, *iScience* **2021**, *24*, 102332.
[3] F. Duffner, L. Mauler, M. Wentker, J. Leker, M. Winter, *Int. J. Prod. Econ.* **2021**, *232*, 107982.
[4] D. Küpper, K. Kuhlmann, S. Wolf, C. Pieper, G. Xu, J. Ahmad, *BCG Global* **2018**.
[5] D. Lucke, C. Constantinescu, E. Westkämper, *The 41st CIRP Conf. on Manufacturing Systems, May 26-28, 2008, Tokyo, Japan* (Eds.: M. Mitsuishi, K. Ueda, F. Kimura), Springer, London, **2008**, pp. 115–118.
[6] T. Günther, N. Billot, J. Schuster, J. Schnell, F. B. Spingler, H. A. Gasteiger, *WGP Congress* **2016**, *1140*, 304.
[7] G. Schuh, J.-P. Prote, A. Gützlaff, K. Thomas, F. Sauermann, N. Rodemann, *Proc. of the 9th Congress of the German Academic Association for Production Technology (WGP), September 30th - October 2nd, Hamburg 2019* (Eds.: J. P. Wulfsberg, W. Hintze, B.-A. Behrens), Springer, Berlin, Heidelberg, **2019**, pp. 533–542.
[8] J. Reis, M. Amorim, N. Melão, Y. Cohen, M. Rodrigues, in *Springer EBook Collection* (Eds.: Z. Anisic, B. Lalic, D. Gracanin), Springer International Publishing; Imprint Springer, Cham, **2020**, pp. 443–456.
[9] J. Pennekamp, R. Glebke, M. Henze, T. Meisen, C. Quix, R. Hai, L. Gleim, P. Niemietz, M. Rudack, S. Knap, et al. in *2019 IEEE Inter. Conf. on Industrial Cyber Physical Systems (ICPS 2019)*. Howards Plaza Hotel Taipei, Taiwan, 06-09 May, 2019, IEEE, Piscataway, NJ, **2019**, pp. 31–37.
[10] International Organization for Standardization, *ISO 9000:2015, Fourth Edition: Quality management systems - Fundamentals and vocabulary*.
[11] G. Riexinger, J. P. Doppler, C. Haar, M. Trierweiler, A. Buss, K. Schöbel, D. Ensling, T. Bauernhansl, *Procedia CIRP* **2020**, *93*, 125.
[12] A. Sommer, M. Leeb, S. Haghi, F. J. Günter, G. Reinhart, *Procedia CIRP* **2021**, *104*, 1011.
[13] J. Wessel, A. Turetskyy, O. Wojahn, C. Herrmann, S. Thiede, *Procedia CIRP* **2020**, *93*, 162.
[14] A. Turetskyy, S. Thiede, M. Thomitzek, N. von Drachenfels, T. Pape, C. Herrmann, *Energy Technol.* **2020**, *8*, 1900136.
[15] E. Ayerbe, M. Berecibar, S. Clark, A. A. Franco, J. Ruhland, *Adv. Energy Mater.* **2021**, 2102696.
[16] C. D. Reynolds, P. R. Slater, S. D. Hare, M. J. Simmons, E. Kendrick, *Mater. Des.* **2021**, *209*, 109971.

[17] Y. S. Zhang, N. E. Courtier, Z. Zhang, K. Liu, J. J. Bailey, A. M. Boyce, G. Richardson, P. R. Shearing, E. Kendrick, D. J. L. Brett, *Adv. Mater.* **2022**, *12*, 2102233.
[18] S. Haghi, H.-C. Töpper, F. J. Günter, G. Reinhart, *Procedia CIRP* **2021**, *104*, 1155.
[19] D. T. Ross, K. E. Schoman, *IEEE Trans. Software Eng.* **1977**, *SE-3*, 6.
[20] B. Nuseibeh, S. Easterbrook, in *ACM Conf.* (Ed.: A. Finkelstein), ACM, New York, NY, **2000**, pp. 35–46.
[21] *ISO/IEC/IEEE International Standard - Systems and software engineering – Life cycle processes – Requirements engineering,* IEEE, Piscataway, NJ, USA.
[22] Department of Defense (Ed.), *Manufacturing Readiness Level Deskbook*, Prepared by the OSD Manufacturing Technology Program in Collaboration with The Joint Service/Industry MRL Working Group **2020**, https://www.dodmrl.com/MRL%20Deskbook%20V2020.pdf.
[23] A. de Carolis, M. Macchi, E. Negri, S. Terzi, in *IFIP Advances In Information And Communication Technology* (Eds.: H. Lödding, R. Riedel, K.-D. Thoben, G. von Cieminski, D. Kiritsis), Vol. *513*, Springer, Cham, **2017**, pp. 13–20.
[24] M. Keppeler, H.-Y. Tran, W. Braunwarth, *Energy Technol.* **2021**, *9*, 2100132.
[25] *Qualitative Research Kit*, (Ed.: U. Flick), SAGE Publ, London, **2007**.
[26] J. Greene, *Advances in mixed-method evaluation. The challenges and benefits of integrating diverse paradigms*, Jossey-Bass Publishers, San Francisco **1997**.
[27] S. D. Eppinger, *Design Structure Matrix Methods And Applications*, MIT Press, Cambridge, MA **2012**.
[28] T. U. Pimmler, *Integration Analysis of Product Decompositions*, Sloan School of Management, Massachusetts Institute of Technology, Cambridge, Massachusetts **1994**.
[29] N. Nitta, F. Wu, J. T. Lee, G. Yushin, *Mater. Today* **2015**, *18*, 252.
[30] H. Y. Tran, C. Täubert, M. Wohlfahrt-Mehrens, *Prog. Solid State Chem.* **2014**, *42*, 118.
[31] V. Wenzel, H. Nirschl, D. Nötzel, *Energy Technol.* **2015**, *3*, 692.
[32] Y. Sato, T. Nakano, K. Kobayakawa, T. Kawai, A. Yokoyama, *J. Power Sources* **1998**, *75*, 271.
[33] L. Bläubaum, F. Röder, C. Nowak, H. S. Chan, A. Kwade, U. Krewer, *ChemElectroChem* **2020**, *7*, 4755.
[34] P.-C. Tsai, B. Wen, M. Wolfman, M.-J. Choe, M. S. Pan, L. Su, K. Thornton, J. Cabana, Y.-M. Chiang, *Energy Environ. Sci.* **2018**, *11*, 860.
[35] J. Li, C. Daniel, D. L. Wood, in *Handbook of Battery Materials* (Ed.: C. Daniel), Wiley-VCH, Weinheim, **2011**, pp. 939–957.
[36] B. L. Mehdi, A. Stevens, J. Qian, C. Park, W. Xu, W. A. Henderson, J.-G. Zhang, K. T. Mueller, N. D. Browning, *Sci. Rep.* **2016**, *6*, 34267.
[37] Z. Chen, J. Wang, J. Huang, T. Fu, G. Sun, S. Lai, R. Zhou, K. Li, J. Zhao, *J. Power Sources* **2017**, *363*, 168
[38] R. Jung, R. Morasch, P. Karayaylali, K. Phillips, F. Maglia, C. Stinner, Y. Shao-Horn, H. A. Gasteiger, *J. Electrochem. Soc.* **2018**, *165*, A132.
[39] V. Wenzel, R. S. Moeller, H. Nirschl, *Energy Technol.* **2014**, *2*, 176.
[40] N. Lingappan, L. Kong, M. Pecht, *Renewable Sustainable Energy Rev.* **2021**, *147*, 111227.
[41] S. Lim, S. Kim, K. H. Ahn, S. J. Lee, *J. Power Sources* **2015**, *299*, 221.
[42] H. Chen, M. Ling, L. Hencz, H. Y. Ling, G. Li, Z. Lin, G. Liu, S. Zhang, *Chem. Rev.* **2018**, *118*, 8936.
[43] Y. Shi, X. Zhou, G. Yu, *Acc. Chem. Res.* **2017**, *50*, 2642.
[44] S.-L. Chou, Y. Pan, J.-Z. Wang, H.-K. Liu, S.-X. Dou, *Phys. Chem. Chem. Phys.* **2014**, *16*, 20347.
[45] J.-T. Li, Z.-Y. Wu, Y.-Q. Lu, Y. Zhou, Q.-S. Huang, L. Huang, S.-G. Sun, *Adv. Energy Mater.* **2017**, *7*, 1701185.
[46] G. Liu, H. Zheng, X. Song, V. S. Battaglia, *J. Electrochem. Soc.* **2012**, *159*, A214.
[47] A. Cushing, T. Zheng, K. Higa, G. Liu, *Polymers* **2021**, *13*, 4033.
[48] J. Kaiser, V. Wenzel, H. Nirschl, B. Bitsch, N. Willenbacher, M. Baunach, M. Schmitt, S. Jaiser, P. Scharfer, W. Schabel, *Chem. Ing. Technol.* **2014**, *86*, 695.
[49] W. Bauer, *Keram. Z.* **2019**, *71*, 42.
[50] E. Ligneel, B. Lestriez, A. Hudhomme, D. Guyomard, *J. Electrochem. Soc.* **2007**, *154*, A235.
[51] L. Ouyang, Z. Wu, J. Wang, X. Qi, Q. Li, J. Wang, S. Lu, *RSC Adv.* **2020**, *10*, 19360.
[52] (Ed.: L. W. McKeen) *Plastics Design Library*, Andrew, Norwich, NY, **2006**.
[53] S. N. Bryntesen, A. H. Strømman, I. Tolstorebrov, P. R. Shearing, J. J. Lamb, O. Stokke Burheim, *Energies* **2021**, *14*, 1406.
[54] P. Zhu, D. Gastol, J. Marshall, R. Sommerville, V. Goodship, E. Kendrick, *J. Power Sources* **2021**, *485*, 229321.
[55] S. W. Kim, K. Y. Cho, *J. Electrochem. Sci. Technol.* **2015**, *6*, 1.
[56] R. Tao, Z. Liang, S. Zhu, L. Yang, L. Ma, W. Song, H. Chen, *Acta Mech. Solida Sin.* **2021**, *34*, 297.
[57] M. Fritsch, M. Coeler, K. Kunz, B. Krause, P. Marcinkowski, P. Pötschke, M. Wolter, A. Michaelis, *Batteries* **2020**, *6*, 60.
[58] N. Billot, T. Günther, D. Schreiner, R. Stahl, J. Kranner, M. Beyer, G. Reinhart, *Energy Technol.* **2020**, *8*, 1801136.
[59] D. Schreiner, M. Oguntke, T. Günther, G. Reinhart, *Energy Technol.* **2019**, *7*, 1900840.
[60] M. Keppeler, S. Roessler, W. Braunwarth, *Energy Technol.* **2020**, *8*, 2000183.
[61] A. C. Martinez, S. Grugeon, D. Cailleu, M. Courty, P. Tran-Van, B. Delobel, S. Laruelle, *J. Power Sources* **2020**, *468*, 228204.
[62] C. A. Heck, M.-W. von Horstig, F. Huttner, J. K. Mayer, W. Haselrieder, A. Kwade, *J. Electrochem. Soc.* **2020**, *167*, 160521.
[63] R. Korthauer, *Lithium-Ion Batteries. Basics and Applications*, Springer, Berlin, **2019**.
[64] W. B. Hawley, J. Li, *J. Energy Storage* **2019**, *25*, 100862.
[65] W. Bauer, D. Nötzel, *Ceram. Int.* **2014**, *40*, 4591.
[66] B. Bitsch, J. Dittmann, M. Schmitt, P. Scharfer, W. Schabel, N. Willenbacher, *J. Power Sources* **2014**, *265*, 81.
[67] C. Chae, H.-J. Noh, J. K. Lee, B. Scrosati, Y.-K. Sun, *Adv. Funct. Mater.* **2014**, *24*, 3036.
[68] J. Li, Y. Lu, T. Yang, D. Ge, D. L. Wood, Z. Li, *iScience* **2020**, *23*, 101081.
[69] D. L. Wood, J. D. Quass, J. Li, S. Ahmed, D. Ventola, C. Daniel, *Drying Technol.* **2018**, *36*, 234.
[70] H. Bockholt, W. Haselrieder, A. Kwade, *ECS Trans.* **2013**, *50*, 25.
[71] M. Baunach, S. Jaiser, S. Schmelzle, H. Nirschl, P. Scharfer, W. Schabel, *Drying Technol.* **2016**, *34*, 462.
[72] W. Haselrieder, S. Ivanov, H. Y. Tran, S. Theil, L. Froböse, B. Westphal, M. Wohlfahrt-Mehrens, A. Kwade, *Prog. Solid State Chem.* **2014**, *42*, 157.
[73] B. Westphal, H. Bockholt, T. Gunther, W. Haselrieder, A. Kwade, *ECS Trans.* **2015**, *64*, 57.
[74] K. M. Kim, W. S. Jeon, I. J. Chung, S. H. Chang, *J. Power Sources* **1999**, *83*, 108.
[75] L. Hoffmann, J.-K. Grathwol, W. Haselrieder, R. Leithoff, T. Jansen, K. Dilger, K. Dröder, A. Kwade, M. Kurrat, *Energy Technol.* **2020**, *8*, 1900196.
[76] B. G. Westphal, A. Kwade, *J. Energy Storage* **2018**, *18*, 509.
[77] M. Wang, D. Dang, A. Meyer, R. Arsenault, Y.-T. Cheng, *J. Electrochem. Soc.* **2020**, *167*, 100518.
[78] D. Liu, L.-C. Chen, T.-J. Liu, T. Fan, E.-Y. Tsou, C. Tiu, *ACES* **2014**, *04*, 515.
[79] C. Schilde, C. Mages-Sauter, A. Kwade, H. P. Schuchmann, *Powder Technol.* **2011**, *207*, 353–.
[80] V. Wenzel, H. Nirschl, D. Nötzel, *Energy Technol.* **2015**, *3*, 692.
[81] A. Kraytsberg, Y. Ein-Eli, *Adv. Energy Mater.* **2016**, *6*, 1600655.

[82] E. Ligneel, B. Lestriez, D. Guyomard, *J. Power Sources* **2007**, *174*, 716.
[83] J. Li, J. Fleetwood, W. B. Hawley, W. Kays, *Chem. Rev.* **2022**, *122*, 903.
[84] J. Li, C. Daniel, D. L. Wood, in *Handbook of Battery Materials*, John Wiley & Sons, Ltd, **2011**, pp. 939–960.
[85] W. B. Hawley, J. Li, *J. Energy Storage* **2019**, *26*, 100994.
[86] W. Haselrieder, S. Ivanov, H. Y. Tran, S. Theil, L. Froböse, B. Westphal, M. Wohlfahrt-Mehrens, A. Kwade, *Prog. Solid State Chem.* **2014**, *42*, 157.
[87] B. Bitsch, N. Willenbacher, V. Wenzel, S. Schmelzle, H. Nirschl, *Chem. Ing. Technol.* **2015**, *87*, 466.
[88] H. Dreger, W. Haselrieder, A. Kwade, *J. Energy Storage* **2019**, *21*, 231.
[89] D.-W. Chung, M. Ebner, D. R. Ely, V. Wood, R. Edwin García, *Modell. Simul. Mater. Sci. Eng.* **2013**, *21*, 74009.
[90] W. Haselrieder, B. Westphal, H. Bockholt, A. Diener, S. Höft, A. Kwade, *Int. J. Adhes. Adhes.* **2015**, *60*, 1.
[91] K. C. Kil, G. Y. Kim, C.-W. Cho, M. D. Lim, K. Kim, K.-M. Jeong, J. Lee, U. Paik, *Electrochim. Acta* **2013**, *111*, 946.
[92] R. Dominko, M. Gaberscek, J. Drofenik, M. Bele, S. Pejovnik, J. Jamnik, *J. Power Sources* **2003**, *119–121*, 770.
[93] K. Y. Cho, Y. I. Kwon, J. R. Youn, Y. S. Song, *Mater. Res. Bull.* **2013**, *48*, 2922.
[94] E. Ligneel, B. Lestriez, D. Guyomard, *J. Power Sources* **2007**, *174*, 716.
[95] W. Bauer, D. Nötzel, V. Wenzel, H. Nirschl, *J. Power Sources* **2015**, *288*, 359.
[96] N. Billot, T. Günther, D. Schreiner, R. Stahl, J. Kranner, M. Beyer, G. Reinhart, *Energy Technol.* **2020**, *8*, 1801136.
[97] W. Bauer, F. A. Çetinel, M. Müller, U. Kaufmann, *Electrochim. Acta* **2019**, *317*, 112.
[98] M. Keppeler, H.-Y. Tran, W. Braunwarth, *Energy Technol.* **2021**, *9*, 2100132.
[99] D. Mohanty, E. Hockaday, J. Li, D. K. Hensley, C. Daniel, D. L. Wood, *J. Power Sources* **2016**, *312*, 70.
[100] D. Liu, L.-C. Chen, T.-J. Liu, W.-B. Chu, C. Tiu, *Energy Technol.* **2017**, *5*, 1235.
[101] R. Diehm, J. Kumberg, C. Dörrer, M. Müller, W. Bauer, P. Scharfer, W. Schabel, *Energy Technol.* **2020**, *8*, 1901251.
[102] Y.-R. Chang, H.-M. Chang, C.-F. Lin, T.-J. Liu, P.-Y. Wu, *J. Colloid Interface Sci.* **2007**, *308*, 222.
[103] M. Schmitt, P. Scharfer, W. Schabel, *J. Coat. Technol. Res.* **2014**, *11*, 57.
[104] S. M. Raupp, M. Schmitt, A.-L. Walz, R. Diehm, H. Hummel, P. Scharfer, W. Schabel, *J. Coat. Technol. Res.* **2018**, *15*, 899.
[105] E. Gutoff, E. Cohen, *Coating and Drying Defects*, John Wiley & Sons, New Jersey **2006**.
[106] M. Schmitt, M. Baunach, L. Wengeler, K. Peters, P. Junges, P. Scharfer, W. Schabel, *Chem. Eng. Process. Process Intensif.* **2013**, *68*, 32.
[107] S. Jaiser, M. Müller, M. Baunach, W. Bauer, P. Scharfer, W. Schabel, *J. Power Sources* **2016**, *318*, 210.
[108] S. Jaiser, A. Friske, M. Baunach, P. Scharfer, W. Schabel, *Drying Technol.* **2017**, *35*, 1266.
[109] H. Dreger, H. Bockholt, W. Haselrieder, A. Kwade, *J. Electron. Mater.* **2015**, *44*, 4434.
[110] N. Susarla, S. Ahmed, D. W. Dees, *J. Power Sources* **2018**, *378*, 660.
[111] J. Kumberg, M. Baunach, J. C. Eser, A. Altvater, P. Scharfer, W. Schabel, *Energy Technol.* **2021**, *9*, 2100549.
[112] E. Oppegård, A. Jinasena, A. Hammer Strømman, J. Are Suul, O. Stokke Burheim, in *Linköping Electronic Conf. Proceedings*, Linköping University Electronic Press, virtual conference, **2021**.
[113] W. Haselrieder, B. Westphal, H. Bockholt, A. Diener, S. Höft, A. Kwade, *Int. J. Adhes. Adhes.* **2015**, *60*, 1.
[114] J. Chen, J. Liu, Y. Qi, T. Sun, X. Li, *J. Electrochem. Soc.* **2013**, *160*, A1502.
[115] M. Indrikova, S. Grunwald, F. Golks, A. Netz, B. Westphal, A. Kwade, *J. Electrochem. Soc.* **2015**, *162*, A2021.
[116] T. Günther, D. Schreiner, A. Metkar, C. Meyer, A. Kwade, G. Reinhart, *Energy Technol.* **2020**, *8*, 1900026.
[117] D. Schreiner, M. Oguntke, T. Günther, G. Reinhart, *Energy Technol.* **2019**, *7*, 1900840.
[118] W. Haselrieder, S. Ivanov, D. K. Christen, H. Bockholt, A. Kwade, *ECS Trans.* **2013**, *50*, 59.
[119] C. Meyer, H. Bockholt, W. Haselrieder, A. Kwade, *J. Mater. Process. Technol.* **2017**, *249*, 172.
[120] C. Meyer, M. Weyhe, W. Haselrieder, A. Kwade, *Energy Technol.* **2020**, *8*, 1900175.
[121] D. Mayer, A.-K. Wurba, B. Bold, J. Bernecker, A. Smith, J. Fleischer, *Processes* **2021**, *9*, 2009.
[122] A. M. Gitis, H. H. Heimes, S. Wessel, D. U. Sauer, A. Kampker, M. Wazifehdust, E. Figgemeier, *Galvanotechnik : älteste Fachzeitschrift Für Die Praxis Der Oberflächentechnik*, Galvanotechnik, Bad Saulgau **2017**, p. 108.
[123] G. Lenze, F. Röder, H. Bockholt, W. Haselrieder, A. Kwade, U. Krewer, *J. Electrochem. Soc.* **2017**, *164*, A1223.
[124] E. N. Primo, M. Chouchane, M. Touzin, P. Vazquez, A. A. Franco, *J. Power Sources* **2021**, *488*, 229361.
[125] H. Kang, C. Lim, T. Li, Y. Fu, B. Yan, N. Houston, V. de Andrade, F. de Carlo, L. Zhu, *Electrochim. Acta* **2017**, *232*, 431.
[126] F. Huttner, A. Diener, T. Heckmann, J. C. Eser, T. Abali, J. K. Mayer, P. Scharfer, W. Schabel, A. Kwade, *J. Electrochem. Soc.* **2021**, *168*, 90539.
[127] B. A. Kitchenham, D. Budgen, O. P. Brereton, *Int. conf. Eval. Assess. Softw. Engr. (EASE)*, Keele **2010**.
[128] B. A. Kitchenham, D. Budgen, O. Pearl Brereton, *Inf. Software Technol.* **2011**, *53*, 638.
[129] A. Witzel, H. Reiter, *The Problem-Centred Interview. Principles And Practice*, Sage, Los Angeles, London, New Delhi, Singapore, Washington DC, **2012**.
[130] A. Bogner, B. Littig, W. Menz, *Interviews Mit Experten. Eine Praxisorientierte Einführung*, Springer VS, Wiesbaden, **2014**.
[131] J. Stapleton, *DSDM, Dynamic Systems Development Method. The Method In Practice*, Addison-Wesley, Harlow, **1998**.
[132] V. Mahajan, H. A. Linstone, M. Turoff, *J. Marketing Res.* **1976**, *13*, 317.