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Traceability of Product and Process Data in the Manufacturing of Lithium-Ion Battery Cells

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Editors‘ Preface

In times of global challenges, such as climate change, the transformation of mobility, and an ongoing demographic change, production engineering is crucial for the sustainable advancement of our industrial society. The impact of manufacturing companies on the environment and society is highly dependent on the equipment and resources employed, the production processes applied, and the established manufacturing organization. The company's full potential for corporate success can only be taken advantage of by optimizing the interaction between humans, operational structures, and technologies. The greatest attention must be paid to becoming as resource-saving, efficient, and resilient as possible to operate flexibly in the volatile production environment.

Remaining competitive while balancing the varying and often conflicting priorities of sustainability, complexity, cost, time, and quality requires constant thought, adaptation, and the development of new manufacturing structures. Thus, there is an essential need to reduce the complexity of products, manufacturing processes, and systems. Yet, at the same time, it is also vital to gain a better understanding and command of these aspects.

The research activities at the Institute for Machine Tools and Industrial Management (*iwb*) of the Technical University of Munich (TUM) aim to continuously improve product development and manufacturing planning systems, manufacturing processes, and production facilities. A company's organizational, manufacturing, and work structures, as well as the underlying systems for order processing, are developed under strict consideration of employee-related requirements and sustainability issues. However, the use of computer-aided and artificial intelligence-based methods and the necessary increasing degree of automation must not lead to inflexible and rigid work organization structures. Thus, questions concerning the optimal integration of ecological and social aspects in all planning and development processes are of utmost importance.

The volumes published in this book series reflect and report the results from the research conducted at *iwb*. Research areas covered span from the design and development of manufacturing systems to the application of technologies in manufacturing and assembly. The management and operation of manufacturing systems, quality assurance, availability, and autonomy are overarching topics affecting all areas of our research. In this series, the latest results and insights from our application-oriented research are published, and it is intended to improve knowledge transfer between academia and a wide industrial sector.

Rüdiger Daub *Gunther Reinhart* *Michael Zäh*

Preface

This dissertation was developed during my employment as a research associate at the Institute for Machine Tools and Industrial Management (*iwb*) at the Technical University of Munich (TUM). Its completion would not have been possible without the support and contributions of many individuals, to whom I would like to express my sincere gratitude.

First and foremost, I would like to thank Prof. Dr.-Ing. Rüdiger Daub for giving me the opportunity to pursue my doctoral studies and for his outstanding supervision over the years. His expert guidance, valuable advice, and constructive feedback were essential to the successful completion of this dissertation. I am also deeply grateful to Prof. Dr.-Ing. Gunther Reinhart and Prof. Dr.-Ing. Michael Zäh for their continuous support and for their dedication to fostering an excellent and inspiring research environment at the *iwb*. Furthermore, I would like to thank Prof. Dr.-Ing. Franz Dietrich for serving as co-advisor to this dissertation and Prof. Dr.-Ing. Christina Reuter for chairing my doctoral thesis defense.

I would like to express my heartfelt thanks to all former colleagues and friends at the *iwb*, especially those from the Battery Production department. I am sincerely grateful for the constant help and support I received, for the valuable technical discussions and exchanges, and for the assistance in conducting the experiments, which would not have been possible without the commitment of my colleagues. The inspiration drawn from working alongside such dedicated researchers, as well as the open, friendly, and collegial atmosphere, made my time at the institute truly exceptional. The years spent at the chair were unforgettable and will continue to shape me both professionally and personally for a lifetime.

My special thanks go to Manuel Ank and Sophie Grabmann for their careful review of this dissertation and for their insightful comments and corrections. I would also like to thank all co-authors of my publications and the students who supported my research with great dedication, both as research assistants and through their thesis projects.

Finally, I would like to express my deepest gratitude to my family and friends, who were always there for me and supported me whenever I needed them. Their unwavering encouragement, continuous support, and understanding throughout this academic journey made the successful completion of this dissertation possible.

Alessandro Maximilian Sommer

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List of Abbreviations

1D	One-dimensional
2D	Two-dimensional
BMS	Battery management system
CC	Constant current
CE	Coulombic efficiency
CIJ	Continuous inkjet
CMC	Carboxymethyl cellulose
CRISP-DM	Cross-industry standard process for data mining
CV	Constant voltage
DEI	Defect evaluation index
DIN	German Institute for Standardization (German: Deutsches Institut für Normung)
DMC	Data Matrix code
DOD	Drop-on-demand
DRM	Design Research Methodology
EOL	End of life
ES	Electrode section
EV	Electric vehicle
IPCC	Intergovernmental Panel on Climate Change
iwb	Institute for Machine Tools and Industrial Management (German: Institut für Werkzeugmaschinen und Betriebswissenschaften of Technical University of Munich (TUM))
LAM	Loss of active material
LAM_a	Loss of active material of anode
LAM_c	Loss of active material of cathode

LIB	Lithium-ion battery
LLI	Loss of lithium inventory
ML	Machine learning
N/P	Negative-to-positive
NMC	Lithium nickel manganese cobalt oxide
NMP	N-methyl-2-pyrrolidone
OCR	Optical character recognition
OCV	Open circuit voltage
OEE	Overall equipment effectiveness
P	Publication
PVDF	Polyvinylidene difluoride
QR	Quick response
RFID	Radio-frequency identification
SBR	Styrene-butadiene rubber
SEI	Solid electrolyte interphase
SM	Solution module
SO	Sub-objective
SOC	State of charge
SOH	State of health
TRU	Traceable resource unit
TUM	Technical University of Munich
ZSW	Center for Solar Energy and Hydrogen Research Baden-Württemberg (German: Zentrum für Sonnenenergie- und Wasserstoff-Forschung Baden-Württemberg)

List of Symbols

Variable	Unit	Description
C	h^{-1}	C-Rate
ΔE_0	V	Difference of the equilibrium potentials
$E_{\mathrm{Anode,0}}$	V	Anode potential at equilibrium
$E_{\mathrm{Cathode,0}}$	V	Cathode potential at equilibrium
I_{ch}	A	Charge current
I_{dis}	A	Discharge current
Q	Ah	Capacity
Q_0	Ah	Nominal capacity
Q_{ch}	Ah	Charge capacity
Q_{dis}	Ah	Discharge capacity
Q_{max}	Ah	Maximum available capacity
$\widehat{U}$	V	Average discharge voltage
U_0	V	Open circuit voltage

1 Introduction

“I’ve studied now Philosophy,
And Jurisprudence, Medicine,
And even, alas! Theology,
From end to end, with labor keen.
And here, poor fool! With all my lore,
I stand, no wiser than before!”

(Johann Wolfgang von Goethe (1749–1832), Faust. A Tragedy,
translated by Bayard Taylor in 1870)

The selected quote by Johann Wolfgang von Goethe highlights, even in his time, that studying all scientific disciplines does not necessarily lead to comprehensive understanding. It underscores the idea that one remains a perpetual learner in the quest for truth, as the mysteries of life cannot be fully explained through facts and research alone.

1.1 Motivation

The Intergovernmental Panel on Climate Change (IPCC) has reported an ongoing worldwide increase in anthropogenic greenhouse gas emissions in their sixth assessment report in 2023, which significantly contributes to climate change (IPCC 2023). As part of global efforts to reduce greenhouse gas emissions, the mobility sector is witnessing a significant shift from fossil-fueled vehicles to electric vehicles (EV) to mitigate carbon dioxide. This transition has directly led to a rapid rise in the global demand for lithium-ion batteries (LIB), which provide the energy storage for the drive system (MOHAMMADI & SAIF 2023). The decarbonization of the energy sector is driving greater use of wind and solar energy, necessitating efficient energy storage, with batteries playing a key role in storing and releasing surplus energy due to their natural volatility (LEHTOLA & ZAHEDI 2019). The growing use of smartphones, laptops, and other portable devices is also contributing to the rising demand for LIBs, as these devices rely on high performance batteries (LIANG ET AL. 2019). In addition, technological advancements in electrochemical energy storage have led to improved battery performance and efficiency, making them increasingly attractive for new applications. This, in turn, further drives the growing demand for batteries, particularly in fields such as aviation (OLABI ET AL. 2023).

The growing demand for batteries, particularly in the context of electromobility and the energy transition, requires massive production capacities (DEGEN ET AL. 2023). This development poses significant challenges for the industry, as battery production is not only resource-intensive but also technically demanding (MAULER ET AL. 2021b). A key cost driver in battery production lies in the materials used. High-quality and expensive raw materials such as lithium, cobalt, and nickel significantly increase production costs (SCHMUCH ET AL. 2018). At the same time, production processes are lengthy, complex, and require high precision and quality standards, making the establishment of efficient manufacturing systems challenging. A particularly critical challenge is the lack of understanding regarding the causes of production fluctuations and the interactions between process parameters and material properties (WESTERMEIER ET AL. 2013). These knowledge gaps lead to variable production quality and high scrap rates, resulting in substantial economic losses, primarily due to the significant costs associated with the high-value streams inherent in battery manufacturing. (KWADE ET AL. 2018)

To address these challenges, the consistent tracing of product and process data presents a promising solution. Traceability systems enable detailed tracking of materials and processes across the entire production chain. This comprehensive approach allows for the early detection and resolution of defects, aiming to minimize production inefficiencies and reduce costs. By leveraging such systems, manufacturers can enhance process transparency, improve quality control, and drive efficiency in battery production. While concepts for product traceability have already been implemented and proven effective in other industries, such as the food (PIZZUTI ET AL. 2014) or pharmaceutical (ROTUNNO ET AL. 2014) sector, there is still a need for suitable methods in the field of battery cell production.

1.2 Objective

The aim of this thesis is to demonstrate that the integration of a traceability system into the production process chain of battery cells enables the identification of defective intermediate products and the implementation of targeted quality measures. Achieving this objective requires the allocation of product and process data across all production stages, including intermediate and final products. A comprehensive requirements analysis is conducted to capture both the overarching requirements of battery cell production and the specific demands of individual process steps. Based on this analysis, a suitable identification method for individual intermediate products is developed, enabling a data-driven linkage of these products to their associated production data. This is particularly challenging in the continuous processes of electrode production, where the production data structure must be restructured to align with defined intermediate products. The result is a clear connection between product and process data, which is essential for enabling quality control and process optimization.

This approach has two primary use cases: First, it facilitates the identification of intermediate products that deviate from established specifications, preventing their further processing. Second, it enables the analysis of relationships between production data and resulting product quality, fostering a deeper understanding of process interactions and deviations.

The proposed method is validated through the prototypical implementation of a traceability system on the *iwb* research production line for LIBs, demonstrating its applicability and effectiveness in a real-world production environment.

1.3 Methods and Structure of the Dissertation

The content development of the present work is based on the Design Research Methodology (DRM) described by (BLESSING & CHAKRABARTI 2009). This methodology is a structured, multi-disciplinary approach that addresses design challenges through systematic research. It combines design processes with research methods to solve problems and generate insights, emphasizing the iterative nature of design and its direct connection to real-world applications. The DRM consists of four phases:

Research Clarification

In the *Research Clarification* phase, the identification and description of the research problem were carried out based on an exploratory literature review. Realistic goals for research and implementation were established, which are summarized in Chapter 1.

Descriptive Study I

In the *Descriptive Study I* phase, the necessary foundations for this work were laid out through a systematic literature review, which is outlined in Chapters 2 and 3. This review covered the fundamentals of the LIB, its manufacturing processes, and important terminology and parameter definitions. Furthermore, the topic of traceability was discussed in general, highlighting crucial definitions, delineations, technical aspects, application areas, and use cases. Finally, the state of the art was discussed and the research gap identified.

Prescriptive Study

During the *Prescriptive Study* phase, results were obtained through empirical studies that demonstrate the gradual integration of a traceability system. Possible identification methods for intermediate and final products were highlighted and discussed. Additionally, a traceability system was designed and implemented, and its validation was demonstrated. The results, presented in the form of successive publications, are provided in Chapter 4.

Descriptive Study II

In the *Descriptive Study II* phase, the developed solutions were evaluated. Through the results in Chapter 4, it was demonstrated how the implementation of a traceability system in battery cell production enables two potential applications. The created database could be used to identify potential defects and revealed previously unknown process-product interactions. Additionally, a critical reflection on the results and a discussion of their transferability to industry are provided in Chapter 5.

In Chapter 6, a final summary of the findings of this work and an outlook on future research topics are provided. The DRM applied for this work is shown in Figure 1.

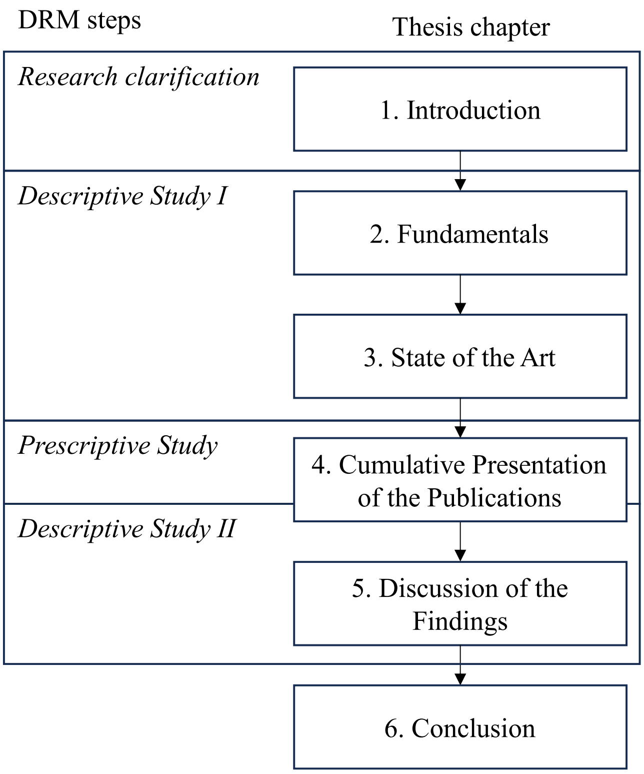

Figure 1: Schematic representation of the applied research methodology based on BLESSING and CHAKRABARTI (2009) with reference to the structure of this work.

2 Fundamentals

2.1 Chapter Outline

This chapter introduces the fundamentals relevant for understanding this work. It begins with an overview of the structure and functionality of LIBs. The manufacturing process is detailed, covering key process steps and essential performance indicators. The chapter explores traceability systems by defining key terms, explaining their technical components, and emphasizing their importance in quality control, process optimization, and regulatory compliance. Practical applications and use cases are presented to illustrate their implementation.

2.2 Lithium-Ion Battery Cells

A LIB cell is a galvanic element that enables the storage of electrical energy with high efficiency and high energy (WINTER & BRODD 2004). According to DIN 40729:1985-05, it is defined as "(...) an energy storage device that can store supplied electrical energy as chemical energy and release it as electrical energy when needed." Electrochemical energy converters are divided into two main categories: primary and secondary cells. Primary cells are non-reversible systems, where energy conversion occurs only in one direction, from chemical to electrical energy, and are commonly known as batteries. In contrast, secondary cells allow for reversible energy conversion, meaning they can convert chemical energy into electrical energy during discharge and electrical energy back into chemical energy during charging. These are referred to as secondary batteries or accumulators. (BARAK 1980, pp. 1–5)

The terms *cell* and *battery* are often used interchangeably, but technically, a cell is the smallest unit of a galvanic system, while a battery consists of multiple cells. Following customary usage, the terms *battery* and *cell* are used synonymously in this thesis. In contemporary usage, both terms refer to systems that store and convert chemical energy into electrical energy. However, modern rechargeable systems are technically classified as secondary batteries or lithium-ion accumulators (JOSSEN & WEYDANZ 2019, p. 5). Their specific properties have enabled widespread use in various sectors. In EVs, the high energy density and rapid charging capabilities make them the preferred energy source (LEUTHNER 2018, p. 14). Additionally, surplus energy from renewable sources like wind and solar power is increasingly stored using these systems to maintain grid stability (MESBAHI ET AL. 2014). In medical technology, reliable power is supplied to critical devices such as pacemakers (TAKEUCHI ET AL. 2003, p. 686), while aerospace applications, including satellites and spacecraft, benefit from the high energy density (BARRERA 2023, p. 2). The rising adoption across industries is attributed to performance, reliability, and a relatively low environmental footprint (KATO ET AL. 2019, p. 3).

2.2.1 Structure and Function

A LIB consists of a positive and a negative electrode, a porous separator, an electrolyte, and a casing. The two electrodes are composed of active materials, binders, conductive additives, and if required, further additives (VUORILEHTO 2018, pp. 21–23). The cathode, acting as the positive electrode, consists of a current collector foil, often aluminum, coated with a mixture of active material and binder (WURM ET AL. 2018, pp. 55–57). Cathode materials often consist of lithium metal compounds such as lithium cobalt oxide ($LiCoO_2$), lithium iron phosphate ($LiFePO_4$), or lithium nickel manganese cobalt oxide (NMC) (FERGUS 2010). The structure of the cathode enables efficient absorption and storage of lithium ions during the battery operation. Similarly, the anode, acting as the negative electrode, consists of a current collector such as copper coated with a layer of material capable of absorbing lithium ions during charging, such as graphite or another carbon compound (WU ET AL. 2003). The porous structure of the anode allows lithium ions to enter the material and be stored there during charging. The electrolyte provides the ionic conductivity between the cathode and anode. In LIBs, the electrolyte is liquid and consists of solvents, a conductive salt, and additives. The electrolyte consist, for example, of the conductive salt lithium hexafluorophosphate, the solvents ethylene carbonate and dimethyl carbonate, and the additive vinylene carbonate (ZHANG 2006). The separator is a porous membrane that allows lithium ions to pass through. The separator electrically isolates the cathode and anode, thus preventing a short circuit of the cell. Materials such as polyethylene and polypropylene are used. (ZHANG 2007) In Figure 2, the typical structure of a LIB is presented.

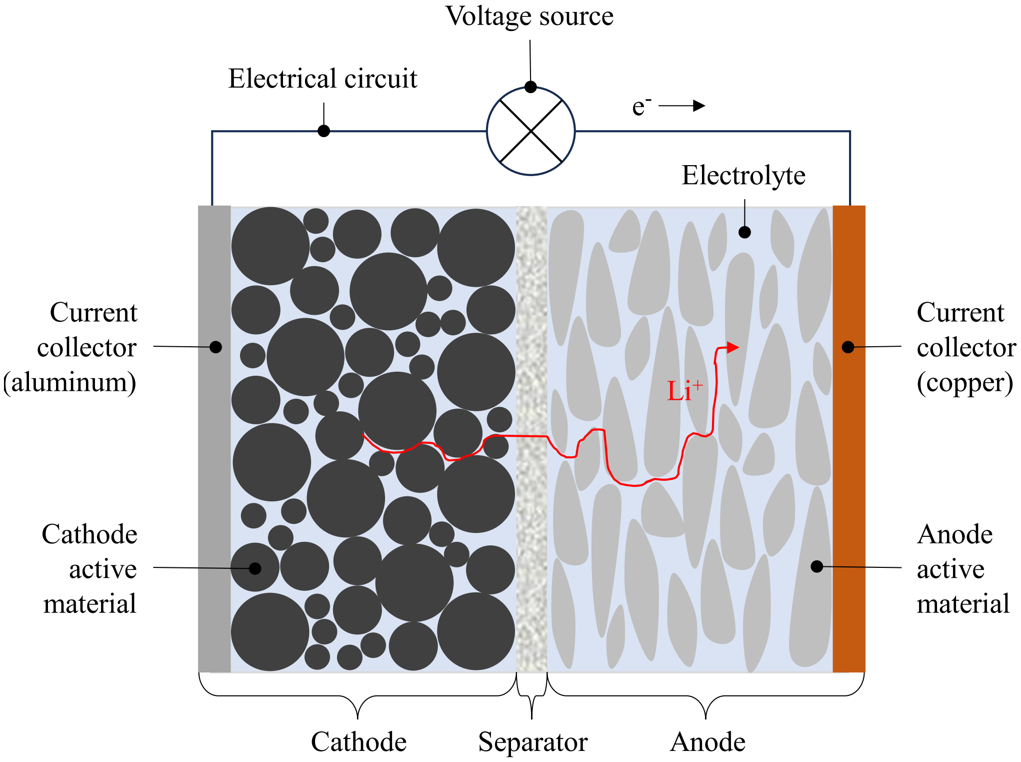

Figure 2: Schematic structure and operating principle of a LIB during the charging process, adapted from VUORILEHTO (2018).

The functional principle of energy storage in rechargeable LIBs is based on the reversible storage and retrieval of lithium ions in the host lattice structures of the active material through electrochemical reactions (STERNER 2016, pp. 201–208). These so-called reduction-oxidation reactions are reversible, occurring in one direction during charging and in the opposite direction during discharging. Oxidation and reduction reactions refer to the release and acceptance of electrons, within the corresponding electrodes named anode and cathode, respectively. This terminology is also applied in LIBs. However, because the electrode names depend on the direction of the reaction, they are typically based on the discharge state of the LIB. During the discharging process, the active material of the negative electrode is oxidized, whereby an electron is released to the consumer circuit and can be used to perform electrical work. A lithium ion is removed from the host lattice of the active material and migrates from the negative electrode (anode) through the electrolyte and the separator to the positive electrode (cathode). At the positive electrode, the lithium ion is reduced at the active material. During the charging process, the reaction occurs in the opposite direction, with electrons being supplied through the external circuit to balance the charges. (Julien et al. 2016, p. 12) The reactions that occur during charging and discharging in a LIB cell are given in Equation 2.1 for the cathode, in Equation 2.2 for the anode. The composition of the two reactions is presented in Equation 2.3 (Yazami & Touzain 1983).

$$\text{Cathode:} \qquad \mathrm{LiMO_2} \rightleftharpoons \mathrm{Li_{1-x}MO_2} + \mathrm{xLi^+} + \mathrm{xe^-} \tag{2.1}$$

$$\text{Anode:} \qquad \mathrm{C} + \mathrm{xLi^+}\ \mathrm{xe^-} \rightleftharpoons \mathrm{Li_xC} \tag{2.2}$$

$$\text{Total reaction:} \qquad \mathrm{LiMO_2} + \mathrm{C} \rightleftharpoons \mathrm{Li_xC} + \mathrm{Li_{1-x}MO_2} \tag{2.3}$$

$LiMO_2$ represents the metal oxide material, C stands for the carbon-containing material, for example graphite. x is selected on the basis of the molar capacities of the electrode active materials used compared to lithium (Yazami & Touzain 1983). The resulting external cell voltage of a LIB is determined by the potential difference between the active electrode materials used for the cathode and anode (Woehrle 2018, p. 104).

2.2.2 Cell Formats, Battery Modules, and Battery Packs

Different cell formats are employed in various applications based on specific requirements and constraints (Sturm et al. 2020). The primary designs of LIB cells, cylindrical, prismatic, and pouch cells, are defined according to DIN 91252, as shown in Figure 3. Pouch cells are commonly utilized in applications where space and mass are critical factors, such as portable electronics and EVs (Ding et al. 2019). Their flexible packaging allows for efficient utilization of space by allowing customization of cell dimensions (Schmuch et al. 2018). Cylindrical cells, characterized by their robustness and ease of assembly, find widespread use in consumer electronics, power tools, and certain automotive applications (Quinn et al. 2018). Prismatic cells, with their compact and stackable design, are favored in applications where high energy density and efficient space utilization are paramount, including grid energy storage systems and certain EV models (Lundgren et al. 2016). Each cell format offers specific advantages and is chosen based on the specific requirements of the intended application (Pettinger et al. 2018, pp. 220–223).

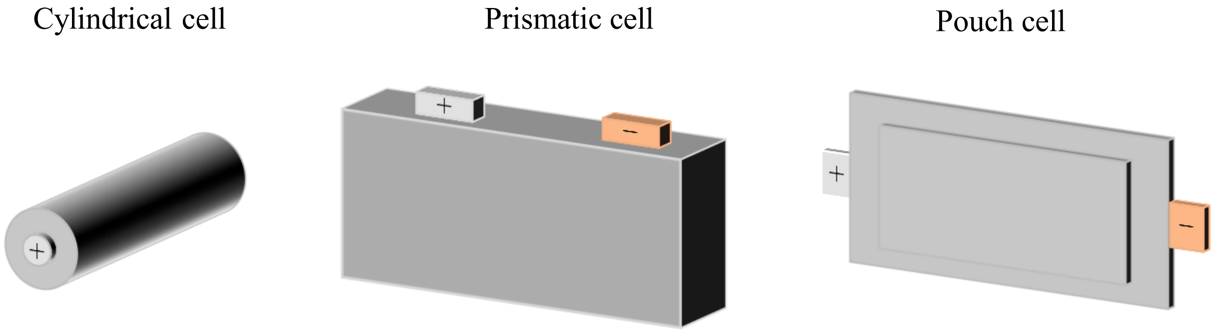

Figure 3: Schematic representation of the three main battery cell formats that are currently used in various applications: cylindrical, prismatic, and pouch cell (from left to right), as defined in DIN 91252.

In a cylindrical cell, the wound electrodes are packed in a metal housing. The advantages of the cylindrical cell are the high robustness, the relatively easy integration of a pressure relief valve and a safety device to switch off the current in the event of a short circuit (KRITZER & NAHRWOLD 2018, p. 120 f.). Conversely, thermal complexities arise due to significant temperature gradients caused by the small surface area of the housing (MOOSAVI ET AL. 2021). Especially at high currents, the cooling capacity is reduced, resulting in spatially varying internal resistance and thus accelerated aging of the cell (WALDMANN & WOHLFAHRT-MEHRENS 2014).

In prismatic cells, the electrodes can either be wound or stacked with isolators placed in between (WOEHRLE 2018). The electrodes are joined inside the cell housing via so-called current collector tabs (PETTINGER ET AL. 2018, p. 217). The housing can be made of steel, aluminum, or plastic. Prismatic cells with metallic housings are extremely robust. This design enables better and more even heat dissipation compared to a cylindrical cell. Individual cells are also interconnected in a spatially efficient manner. However, their energy density is lower than that of a pouch cell due to the additional weight of the housing. (PETTINGER ET AL. 2018, p. 217 f.)

In contrast to cylindrical and prismatic cells, the pouch cell features a cell housing made of composite foil, which consists of an aluminum composite pouch laminated with a polymer. Pouch cells are also known as flat cells or coffee bag cells. The electrodes are assembled in a stack, like those in prismatic cells. Due to the lighter pouch foil, the overall cell mass is lower for the same amount of active material compared to prismatic cells. (PETTINGER ET AL. 2018, p. 217 f.) In addition, the heat capacity of the cell is reduced, making a pouch cell easier to cool (RHEINFELD ET AL. 2020). Moreover, a pouch cell can have a higher energy density than a prismatic cell. The disadvantages of this cell format include the lower mechanical robustness of the pouch foil. The pouch foil is sealed with heat-sealing seams, which can negatively affect the seal's integrity. As a result, the electrolyte may come into contact with humidity, leading to irreversible decomposition of the electrolyte. (PETTINGER ET AL. 2018, p. 217 f.)

In the automotive sector, individual battery cells are connected in series to form battery modules that provide the required voltage. The modules are then assembled to form a pack. (SAW ET AL. 2016) The modules in a pack are typically connected in parallel to achieve a higher current output. When the individual battery cells in a module are connected in parallel, they maintain the same voltage while their currents combine. In a series connection, the voltages of the individual cells add up, while the current through each cell remains the same. (MAHMOUDZADEH

Andwari et al. 2017) In addition to the modules, the battery pack includes a housing that provides protective and cooling functions, as well as a battery management system (BMS). Due to the high sensitivity of LIB modules, they are monitored and protected by the BMS, which handles data communication with the vehicle while measuring and controlling temperature, state of charge (SOC), and voltage. (Pettinger et al. 2018, p. 223)

2.2.3 Battery Cell Production

The production of LIBs can be divided into three process categories that cover all production steps between the raw material and the battery application. These steps are the electrode production, the cell assembly, and the cell finalization (Simon 2018, p. 227). All the necessary production steps are assigned to these groups, as illustrated in Figure 4.

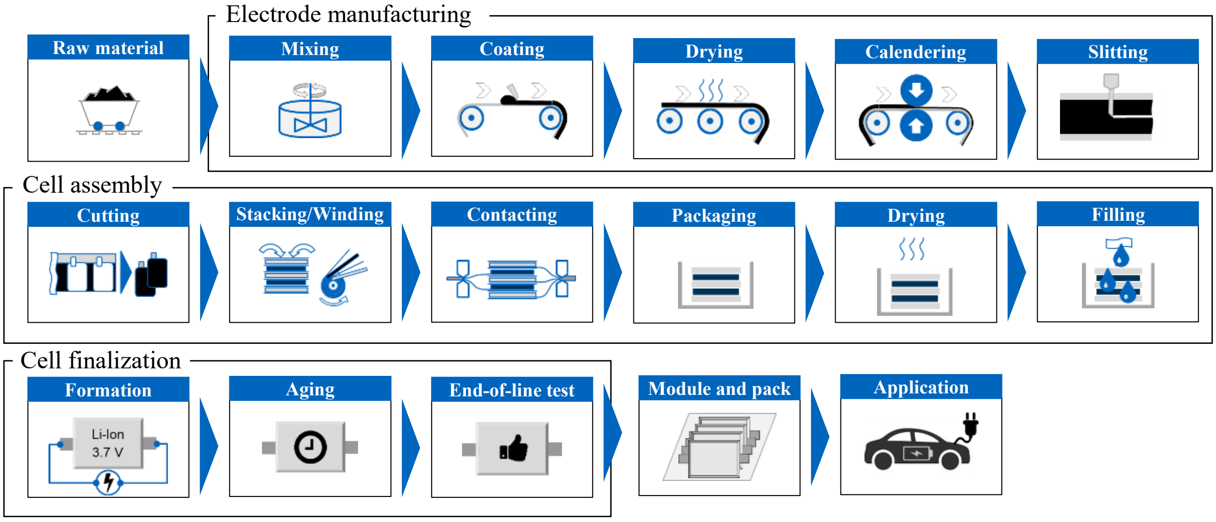

Figure 4: LIB production steps grouped into the electrode production, the cell assembly, and the cell finalization.

Electrode Production

Mixing: The first step in LIB production is the mixing of the raw materials required for electrode production. Depending on the type of electrode and cell chemistry, these materials include the active materials that enable lithium-ion storage, conductive additives to improve electrical conductivity, binders for adhesion and cohesion, solvents for processability, and other additives. All constituents are mixed in several dry and wet mixing steps with different temperatures, atmospheres, and batches. The intermediate product is called slurry (Pettinger et al. 2018, p. 213 f.). Prominent examples of cathode constituents are NMC, carbon black, and polyvinylidene difluoride (PVDF), mixed in the solvent N-methyl-2-pyrrolidone (NMP) (Vuorilehto 2018). For anodes, graphite serves as the active material, carbon black as the conductive additive, carboxymethyl cellulose (CMC), and styrene-butadiene rubber (SBR) as binders. (Vuorilehto 2018, p. 26). The solvent in which the anode components are mixed is water. (Pettinger et al. 2018)

Coating and drying: The second production step involves applying the slurry onto the current collector foil. Typically, an aluminum foil with a thickness of 15 µm to 25 µm is used for cathodes, while a copper foil with a thickness of 6 µm to 12 µm is used for anodes. The coating process is carried out continuously in a roll-to-roll process using slot die coating. Alternatively, the coating methods doctor blade or reverse roll coating can be used. Intermittent coating and double-sided coating represent two different types of coating. Key parameters of the intermediate product include the coating thickness and the areal mass loading, which directly impact the capacity of the LIB. Although drying is listed as the third production step, it occurs immediately after coating within the same roll-to-roll process. Various dryers, each with specific atmospheres, temperatures, and volume flows, are used to remove the solvent from the electrode. (PETTINGER ET AL. 2018)

Calendering: The thickness and porosity of the coated electrode coil are reduced through compression using rollers applying a linear load (PETTINGER ET AL. 2018). This process involves rearranging and utilizing both elastic and plastic deformation of the particles (LU ET AL. 2020). Calendering enhances the cohesion of the active material, impacts the rate capability of a LIB due to changes in porosity, and contributes to increasing the volumetric energy density of a LIB (HASELRIEDER ET AL. 2013).

Slitting: The final process step of electrode manufacturing is slitting, which involves cutting the foil to the required cell variant and size. The anode or cathode coil is inserted into the slitting machine. Initially, continuous cutting takes place in the longitudinal direction of the foil web, resulting in several narrower electrode strips. Subsequently, the electrodes for prismatic and cylindrical cells are cut in the transverse direction to the foil web. The cutting of shorter strips is done according to the dimensions and winding number of the cell. For pouch cells, individual electrode sheets are cut from the electrode strips in the next production step, preparing them for the assembly of the cell components. (HAWLEY & LI 2019, KAMPKER 2014, p. 67 f.)

Cell Assembly

Cutting: In the first step of cell assembly, the coated, dried, and calendered electrode coil is cut into individual electrode sheets (PETTINGER ET AL. 2018, p. 215). Laser cutting is a viable method for electrode cutting. This fabrication method demands special attention to safety, laser focus, and potential impacts from applied heat, particles, and remnants (PFLEGING 2018). Alternatively, mechanical procedures such as punching and die board cutting can be employed to cut the electrode sheets, requiring careful handling of sharp tools to prevent bent edges or smearing of the active material (PETTINGER ET AL. 2018).

Stacking or Winding: In the assembly of pouch cells and stacked prismatic cells, individual cathode and anode sheets are combined with a separator. Two main methods are used to stack these components: Z-folding and single-sheet stacking. In Z-folding, the cathode and anode sheets are inserted sideways into a Z-shaped separator. In single sheet stacking, the layers, anode, cathode, and separator, are alternately stacked. For prismatic cells with wound electrodes or cylindrical cells, stacking is not used. Instead, a winding process is employed after slitting, where different webs are wound around a prismatic core in the following order: cathode, separator, anode, and separator. (PETTINGER ET AL. 2018, p. 215 f., KWADE ET AL. 2018)

Contacting: Following cell stacking or winding, the uncoated edges of the current collector foils are contacted. In pouch cells, the current collectors are welded to cell tabs. However, in cylindrical and prismatic cells, the current collector foil is welded to the contact terminals of the housing. This connection between the current collector foils and the terminals ensures the flow of current. Ultrasonic welding is the method commonly used in industry to make this connection. (KAMPKER 2014, pp. 69–76)

Packaging: After contacting, the cell stack is inserted into the packaging material of the respective cell. Pouch cells are packed in a dense and electrically insulating polymer-aluminum composite foil. For the subsequent electrolyte filling, the pouch cell is sealed on three sides. The cell stacks for cylindrical and prismatic cells are insulated from the housing with a foil. The cell stack is then inserted into the respective housing, and the lid is fixed to the housing using laser beam welding. (KAMPKER 2014, 70-74, 76-77, WOEHRLE 2018, p. 105 f.)

Filling: The cell is filled with electrolyte through the unsealed side or valve under a protective gas atmosphere in a cyclical process. First, the cell is evacuated through the valve opening to create a vacuum, which helps with the initial electrolyte filling. Afterward, the cell is evacuated again and refilled with another batch of electrolyte. This process is repeated several times until the cell is fully filled and the electrolyte is evenly distributed inside the cell. Throughout the process, the cell is hermetically sealed to prevent the escape of volatile components like the solvents of the electrolyte. Additionally, moisture must be prevented from entering the cell to avoid the formation of hydrofluoric acid when it encounters the electrolyte. The filling process requires precise control over the filling rate, batch size, filling pressure, and electrolyte temperature to ensure proper cell function. (KAMPKER 2014, p. 74, PETTINGER ET AL. 2018, p. 218)

Cell Finalization

Formation: This step refers to the first charging and discharging cycles under controlled conditions. During the first cycles, the solid electrolyte interphase (SEI) is formed. The SEI is an interfacial film on the surface of the anode particles and provides protection to the anode from the electrolyte. The formation of the SEI binds lithium ions, resulting in an irreversible capacity loss. (PETTINGER ET AL. 2018, p. 219) Gas generated during the electrochemical processes must be released from the cells. In cylindrical and prismatic cells, this gas escapes through valves. In pouch cells, a gas pocket forms, which is punctured in a vacuum chamber, and the gases are then suctioned out. The resulting space in the pouch cell is then filled with electrolyte, and the cell is sealed. (KAMPKER 2014, pp. 78–80)

Aging: During this process, the LIBs are stored in a temperature-controlled environment for several days. This step is necessary as the long-term performance characteristics of a cell can only be reliably determined after a certain period. The SOC is regularly monitored to detect faulty and underperforming cells that fall below their nominal performance specifications. (KAMPKER 2014, p. 80)

End-of-line test: This inspection involves a series of tests to ensure that the finished LIBs meet quality standards and meet the requirements for use in various applications. These include electrical performance tests, safety tests, leak tests, environmental compatibility tests, and functional tests. The purpose of these tests is to ensure that the LIBs can deliver the required energy, operate safely without causing hazardous situations, and function properly. The end-of-line test is crucial to ensure the quality and reliability of the batteries before they are delivered to customers. (WOLTER ET AL. 2012, PETTINGER 2018, p. 245)

After the cell production phase, the individual cells are assembled into battery modules or battery packs, depending on the following application. Details regarding the subsequent process steps and the components used can be found in respective technical literature.

2.2.4 Battery Performance Characteristics

There are several performance characteristics describe the behavior of LIBs. In the following, the key parameters necessary for a comprehensive characterization and understanding of this thesis are introduced.

Open Circuit and Average Discharge Voltage

The open circuit voltage (OCV) U_0 between the electrodes arises from the difference in potential ΔE_0 of the anode $E_{\text{Anode},0}$ relative to Li/Li$^+$ and the potential of the cathode $E_{\text{Cathode},0}$ relative to Li/Li$^+$ at thermodynamic equilibrium. $E_{\text{Cathode},0}$ and $E_{\text{Anode},0}$ represent the cathode and anode potentials at equilibrium, respectively. In Equation 2.4, the relation between the potential of the electrodes and U_0 is shown. (JULIEN ET AL. 2016, p. 51)

$$U_0 = \Delta E_0 = E_{\text{Cathode},0} - E_{\text{Anode},0} \tag{2.4}$$

The average discharge voltage $\widehat{U}$ refers to the average voltage output of a cell over the duration of one discharge cycle. This value is typically measured or calculated by integrating the voltage over time during discharging and dividing by the total discharge time.

Capacity

The nominal capacity Q_0 signifies the theoretical maximum electrical charge that a cell can store (STERNER & STADLER 2014, p. 218). This value is determined by the specific materials and their quantities within the cell, based on their atomic structure (KORTHAUER 2013, p. 16). Q_0 is the capacity value specified by the manufacturer, determined according to the procedures outlined in the manufacturer's corresponding standard (STERNER & STADLER 2014, p. 218). The actual capacity Q refers to the amount of electric charge available under specific conditions at the beginning or during the battery discharge process. It is affected by several factors, including the current, the cutoff voltage, and the ambient temperature. (KORTHAUER 2013, p. 16)

State of Charge

The SOC indicates the current charge level of a battery relative to its initial capacity. It is defined as the ratio of the remaining capacity Q to the nominal capacity Q_0. SOC is often expressed in percentage, where 100 % corresponds to a fully charged state and 0 % corresponds to a fully discharged state. The calculation for the SOC is given in Equation 2.5. (KURZWEIL & DIETLMEIER 2018, p. 233)

$$SOC = 100\,\% * \frac{Q}{Q_0} \tag{2.5}$$

C-Rate

The rate at which a battery cell is charged or discharged is referred to as the C-rate, as defined in Equation 2.6. This value represents the charging or discharging factor relative to the nominal capacity Q_0, based on the charging current I_{ch} or discharging current I_{dis}. The unit is 1/hour but is commonly denoted simply by the letter *C*. (KURZWEIL & DIETLMEIER 2018, p. 233 f.)

$$C\text{-}rate = \frac{I_{\mathrm{ch}}/I_{\mathrm{dis}}}{Q_0} \tag{2.6}$$

Charging and Discharging Modes

Batteries can be charged and discharged utilizing different methods, such as constant current (CC) and constant voltage (CV) strategies. LIBs are commonly charged using a combination of both, known as CCCV charging. Using this approach, the battery is first charged at a constant C-rate until it reaches a specified voltage level. During the constant voltage (CV) phase, the voltage is held steady until a predefined stop condition is met, such as the current dropping below a specified C-rate threshold (LEUTHNER 2018, p. 16). Figure 5 qualitatively illustrates this CCCV charging strategy with corresponding voltage, current, and SOC curves. In this example, the battery with a capacity of 1 Ah was charged from 2.9 V to 4.2 V during a CC phase with a 2 C rate over 30 minutes, followed by a CV phase where the voltage was held constant while the current decreased rapidly.

Discharging strategies are not discussed within this dissertation as they vary depending on the application. They are typically specified by a maximum allowed CC discharge rate, which depends on factors such as the active materials, the temperature, the lower voltage limit, the SOC, and design of the battery. Moreover, the upper and lower voltage limits for charging and discharging, respectively, are specific for the cell chemistry. Exceeding these voltage and C-rate limits can lead to degradation, damage to the cells, and potentially hazardous events (KOEHLER 2018, pp. 90–94).

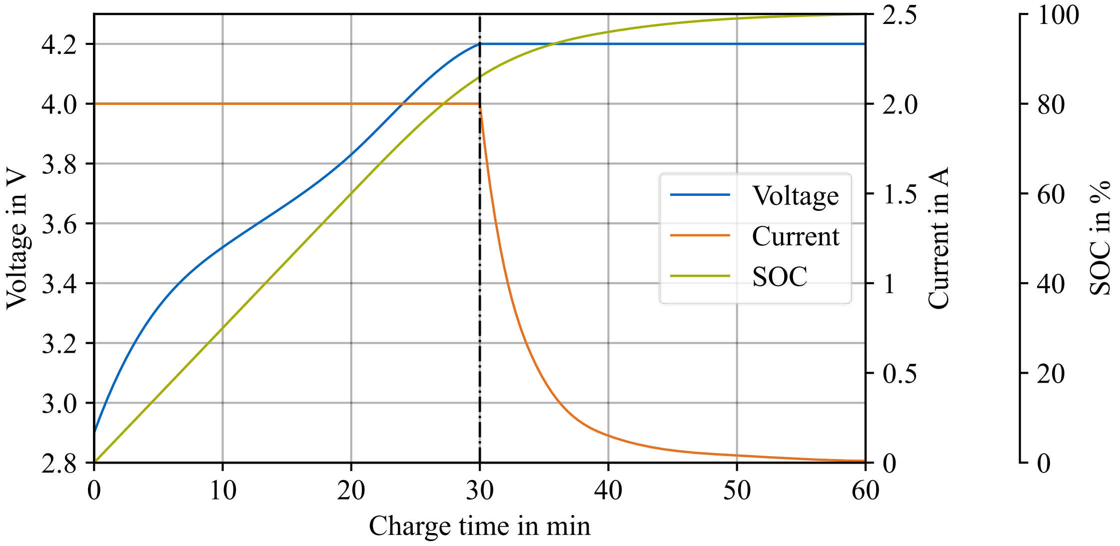

Figure 5: Qualitative curves of the voltage, the current, and the SOC during a CCCV charging process of a battery. The vertical dashed line at 30 min marks the transition from the CC to the CV phase.

During the cycling and the storage of batteries, degradation is inevitable, primarily evidenced by a loss of capacity and an increase in internal resistance (EDGE ET AL. 2021). Battery aging is commonly categorized into calendaric and cyclic aging. Calendaric aging considers the degradation of a battery during periods of non-use, primarily influenced by storage conditions such as the SOC and the temperature (BARRÉ ET AL. 2013). Cyclic aging refers to degradation during the charging and discharging of the battery, which depends on the energy throughput determined by the operating strategy, such as the C-rate, the voltage limits, and the SOC.

State of Health, End of Life, and Coulombic Efficiency

The quantitative assessment of the battery degradation is termed the state of health (SOH), which spans from 0 % to 100 %. The value is determined by comparing the nominal capacity Q_0 of the battery at the start of its life with the maximum available capacity Q_{max} as outlined in Equation 2.7. (KURZWEIL & DIETLMEIER 2018, p. 245)

$$SOH = 100\,\% * \frac{Q_{\mathrm{max}}}{Q_0} \tag{2.7}$$

The end of life (EOL) of batteries is often defined as 80 % SOH (DOS REIS ET AL. 2021). This is used due to practical limits since the LIB becomes unusable the more the SOH fades. A performance metric for describing the capacity retention ability is the coulombic efficiency (CE) (LIN ET AL. 2018). This metric is defined as the ratio between discharge capacity Q_{dis} and charge capacity Q_{ch} by Equation 2.8. (KURZWEIL & DIETLMEIER 2018, p. 29 f.)

$$CE = \frac{Q_{\mathrm{dis}}}{Q_{\mathrm{ch}}} \tag{2.8}$$

In processes involving symmetric strategies for charging and discharging, the CE consistently falls below 100 %. This is due to the inevitable sequestration of certain lithium ions during each cycle, rendering them inaccessible for subsequent utilization. Irreversible capacity loss can result from various factors. Mechanically induced degradation leads to partial loss of cohesion or adhesion in the electrodes (ZHU ET AL. 2020), while structural changes in active materials occur over cycles (SARRE ET AL. 2004). Additionally, significant capacity loss arises from unavoidable surface reactions between active material particles and the electrolyte. On the anode side, a fraction of ions reacts irreversibly with electrolyte components, forming a film on the active material surfaces (AN ET AL. 2016). Cathode materials are also susceptible to irreversible parasitic reactions, such as surface layer formation (BIRKL ET AL. 2017). Additionally, capacity losses can be ascribed to lattice distortion of cathode active materials (SEOK ET AL. 2024). To elucidate the loss of capacity, BIRKL ET AL. (2017) conducted experiments demonstrating various degradation modes commonly reported in the literature. Loss of lithium inventory (LLI) occurs due to the consumption of lithium ions by parasitic reactions such as SEI growth and lithium plating, resulting in capacity fade. Additionally, an increase in surface interfaces can lead to a decrease in capacity. Loss of active material (LAM) occurs in both electrodes, affecting the cathode ($\mathrm{LAM_C}$) and the anode ($\mathrm{LAM_A}$). This loss of active material reduces the active mass available, resulting in capacity and power fade. Factors such as particle cracking, loss of electrical contact, resistive layer blockage, or structural disordering can trigger LAM_C and LAM_A. This can manifest as the loss of lithiated or delithiated active material, potentially resulting in a combination of LAM and LLI. (BIRKL ET AL. 2017)

Capacity tests rely on the established method of fully charging and discharging a battery cell within its specified voltage limits while mathematically integrating the current to obtain the capacity. The resulting available capacity decreases with increasing discharge rate due to overpotentials, thereby reaching voltage limits faster (BARAI ET AL. 2016). Similar effects are observed during charging, though a CV phase typically follows the CC phase to fully charge the battery. Most norms and papers recommend conducting capacity tests at 1 C or C/3 at 25 °C (BARAI ET AL. 2019).

2.3 Traceability Systems

Traceability in production refers to the ability to track the path of a product or batch of raw materials throughout the entire manufacturing process. This involves collecting and documenting information about the origin of raw materials, the processing steps, and the identification of intermediate and final products. (OLSEN & BORIT 2013) Traceability is crucial for the following reasons.

- *Quality assurance*: Traceability plays a critical role in maintaining product quality by enabling the identification of the root cause and extent of any issues that arise. If a defect is discovered, traceability allows manufacturers to pinpoint whether the problem originated from a specific batch of raw materials, a particular production step, or improper handling. This detailed insight helps companies respond swiftly to resolve the issue, limit the number of affected products, and reduce potential impacts on consumers' safety and satisfaction. Furthermore, it helps protect the company's reputation by demonstrating accountability and effective problem management. (JANSEN-VULLERS ET AL. 2003)
- *Safety*: In industries like food and pharmaceuticals, traceability is crucial for quickly addressing safety concerns. If a product is contaminated, traceability allows companies to identify and remove all affected items from the market. This helps prevent harm to consumers, ensures regulatory compliance, and maintains brand trust. (GALLO ET AL. 2021)
- *Legal requirements*: Many industries are required by regulations to maintain traceability throughout production and supply chains. Companies must comply with these regulations to ensure safety, quality, and accountability while avoiding legal consequences such as fines, recalls, and reputational damage. Maintaining traceability is essential for meeting legal standards and protecting the company's reputation. (CHARLEBOIS ET AL. 2014)

2.3.1 Definitions and Differentiations

Traceability

The term *traceability* is used across various fields, resulting in multiple interpretations and definitions. The scientific literature provides several definitions of traceability, highlighting both commonalities and differences. Most definitions characterize traceability as an ability, often described using verbs such as *track* or *trace*. They generally describe that this ability applies to physical objects and extends beyond the boundaries of a single company. However, there is some disagreement regarding the specific verbs used, the definition of a physical object, and the precise scope of traceability. A more detailed examination of the concepts related to traceability is provided below.

According to DIN EN 9000:2015, traceability is described as “the ability to trace the history, application or location of that which is under consideration”. Traceability involves identifying a unit or service and ensuring that relevant information linked to it is accessible throughout the entire production chain.

MOE et al. (1998) define traceability as the ability to track a product batch and its history through all or part of the production chain, from harvest through transport, storage, processing, distribution, and sales, or within any single step of the chain. (MOE 1998)

MCKEAN et al. (2001) explain traceability as the ability to maintain credible custody of identification for animals or animal products through various steps within the food chain, from the farm to the retailer. (MCKEAN 2001)

Regulation (EC) No 178/2002 of the EUROPEAN PARLIAMENT AND OF THE COUNCIL (2002) defines traceability as the ability to trace and follow a food, feed, food-producing animal, or substance intended to be, or expected to be, incorporated into food or feed through all stages of production, processing, and distribution. (EUROPEAN PARLIAMENT & COUNCIL 2002)

VAN DER VORST (2006) describes traceability as the process of documenting and tracing a product (lot) forward and backward, along with its history, through all or part of a production chain, from harvest through transport, storage, processing, distribution, and sales. (VAN DER VORST 2006)

The definitions of traceability share a focus on tracking a product or batch through various stages of the production chain, including harvesting, transport, storage, processing, and distribution. While all emphasize the importance of identifying and documenting relevant product information, they differ in focus and context. Some definitions apply generally to products, while others specifically address animals, animal products, or food-related substances. The EUROPEAN PARLIAMENT AND OF THE COUNCIL (2002) regulation has a legal focus, whereas others, like VAN DER VORST (2006), emphasize the process of documentation. MCKEAN et al. (2001) stress the credibility of identification.

Internal and External Traceability

Internal and external traceability are essential concepts in various industries, particularly in manufacturing, supply chain management, and software development. These concepts are used to track and trace the history, application, or location of products, components, or data throughout their lifecycle. (ISLAM & CULLEN 2021, MOE 1998)

Internal traceability refers to the ability to trace the history, the application, or the location of items within a single organization (MOE 1998). This involves tracking the movement and transformation of products, components, or data as they pass through various production processes and stages within the organization. In a manufacturing context, internal traceability allows a company to track the raw materials, the components, and the finished goods as they move through different stages of production (CHENG & SIMMONS 1994). This includes tracing which batch of raw materials was used to produce a specific product and which machines and processes were involved. In supply chain management, internal traceability involves tracking inventory levels, shipments, and storage locations within a company's warehouses (SHOU ET AL. 2021). In software development, internal traceability refers to tracking changes and updates within the development process, such as linking requirements to code changes, tests, and deployments (CLELAND-HUANG ET AL. 2014).

External traceability refers to the ability to trace the history, application, or location of items across different organizations or stages outside a single company (ISLAM & CULLEN 2021). This involves tracking products, components, or data as they move through the supply chain from suppliers to manufacturers to distributors to customers (SCHUITEMAKER & XU 2020). In manufacturing, external traceability ensures that a company can track the origins of raw materials and components from suppliers, as well as the distribution of finished products to customers (CHENG & SIMMONS 1994). For instance, it can trace which supplier provided a specific batch of materials and where the finished products were shipped. In supply chain management, external traceability involves tracking the flow of goods and information between different entities, such as suppliers, logistics providers, distributors, and retailers (RAZAK ET AL. 2023). In software development, external traceability involve tracking dependencies and integrations with third-party software, libraries, or services (CLELAND-HUANG ET AL. 2014). The key benefits of external traceability include an enhanced ability to recall products and manage risks, improved compliance with industry regulations and standards, greater transparency and trust among supply chain partners, and better coordination and collaboration across the supply chain (ISLAM & CULLEN 2021).

Forward and Backward Traceability

As presented in Figure 6, traceability can be characterized by forward tracking and backward tracing.

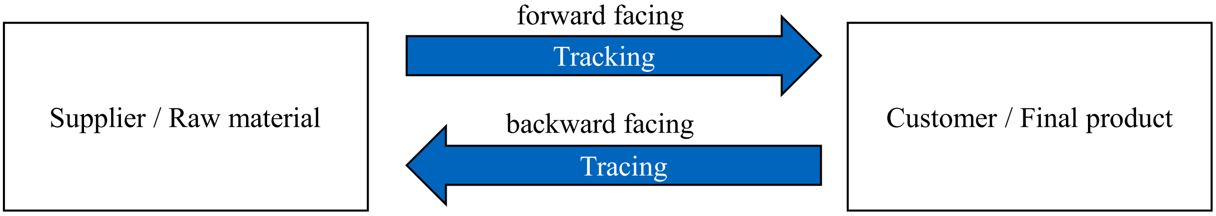

Figure 6: The relationship between tracking and tracing as components of traceability on production; adapted from BOSONA & GEBRESENBET (2013).

Forward traceability refers to the process of identifying the relationships between raw materials and the end products that use them. This involves tracking which final products have incorporated a specific raw material, which shares a common set of properties with other materials. (JANSEN-VULLERS ET AL. 2003) Backward traceability involves tracing the origins of materials used in production. It identifies the raw material lots that were used in the manufacturing of a specific product, and then tracks the source of those materials further back in the supply chain. (JANSEN-VULLERS ET AL. 2003)

Tracking involves documenting all elements and treatment parameters throughout the entire product creation chain, such as determining the position of a component. Information about any production errors that may have occurred can be passed on to a subsequent process step. Furthermore, tracking can optimize the use of available assembly capacities by managing and controlling the material flow. In contrast, tracing helps identify the origin of an individual component or determine the cause of a quality issue or complaint. If a fault can be traced back to a specific element or treatment parameter in a finished product, the combination of tracking and tracing allows for the targeted identification of other components affected by the same issue. This process relies on data stored at specific points during the manufacturing of an object. When combined, forward and backward traceability enables a quick response to product quality deviations and helps uncover complex relationships between quality and production parameters. (FELDMANN ET AL. 2014, p. 841 f.)

Traceability Resource Unit

The traceable resource unit (TRU) refers to the smallest identifiable and unique item that is tracked within a system or process for traceability purposes. TRUs can vary depending on the specific industry or application but generally represent individual units that are monitored throughout the production or supply chain to ensure traceability, quality control, and compliance with regulations. Examples of TRUs are individual products, batches of raw materials, and specific production lots. (KIM ET AL. 1999)

The selection of an appropriate TRU is determined by the specific requirements of the production type. A distinction is drawn between discrete and continuous production. In discrete production, a countable quantity of products is manufactured through distinct process steps (BLÖMER 1999, p. 5). Traceability is not a challenge in this type of production (KVARNSTRÖM & OGHAZI 2008). In continuous production, there is a constant flow of material, with products or materials being further processed across multiple production steps, sometimes transitioning through all three aggregate states (FRANSOO & RUTTEN 1994). The challenges in continuous production with regard to traceability lie in the complexity of process flows, which can occur in parallel, sequentially, in reflux, and without interruption in product treatment (KVARNSTRÖM & OGHAZI 2008). In continuous production, there are no distinct batches. This challenge can be addressed by creating imaginary batches. To achieve this, markings are introduced at uniform intervals within the material flow, effectively segmenting it into batches. The granularity of traceability is determined by the chosen distance between these markings. (KVARNSTRÖM & OGHAZI 2008, AIELLO ET AL. 2015)

Traceability Granularity

Granularity is a term used in various fields, such as tracking the quantity of items in a group, ensuring data accuracy, detailing supply chains, and in software engineering (NOLL & RIBEIRO 2007, KARLSEN ET AL. 2012). In traceability systems, granularity refers to the level of detail in the gathered information about a specific, identifiable or tracking unit (QIAN ET AL. 2017). A tracking unit may not always be a single item; it can also represent a batch or bulk cargo, clearly defined by its associated information. With increasing granularity, more specific data is collected, requiring management and adjustments in identification requirements for each level (KARLSEN ET AL. 2012). The principle of the traceability granularity level depending on its depth is shown in Figure 7.

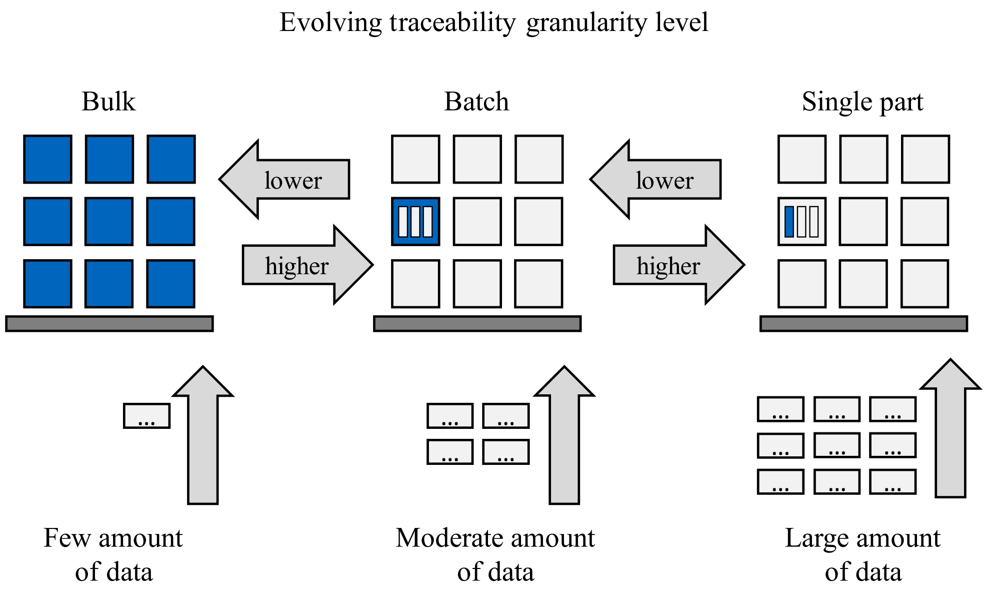

Figure 7: Traceability granularity level from a bulk to single part; adapted from WITTINE ET AL. (2020).

In describing a traceability system in detail, the terms *breadth*, *depth*, *precision*, and *access* are commonly used. *Breadth* quantifies the amount of information and data that a traceability system must record. *Depth* indicates how extensively tracking and tracing can occur throughout the lifecycle of a product. *Precision* measures the certainty of locating the characteristics of a unit, while *access* describes how quickly information is communicated to stakeholders. (BOSONA & GEBRESENBET 2013)

To fully comprehend granularity within the framework of a traceability system, it is imperative to differentiate between the quantity and quality of data. A system with high granularity not only encompasses breadth but also precision. This means that the available data is highly specific and associated with a small number of single parts. Conversely, a system with low granularity links fewer data points to a larger number of units, such as batches or bulk. (WITTINE ET AL. 2020)

2.3.2 Structure of a Traceability System

A traceability system links the physical flow of goods with the corresponding flow of information. It is built around four core elements: *identification*, *data recording*, *data linkage*, and *communication* (FELDMANN ET AL. 2014, p. 845 f.), as shown in Figure 8.

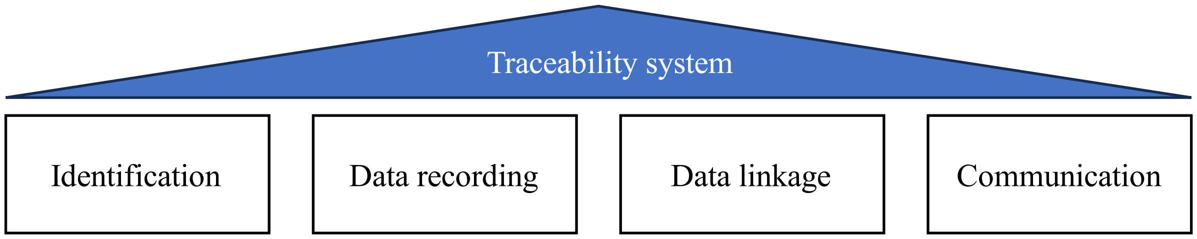

Figure 8: Core elements of a traceability system; adapted from WEGNER-HAMBLOCH & SPRINGOB (2004).

Identification: To ensure effective traceability, it must be possible to unambiguously identify both the units, and all parties involved in the supply and value chain, without overlaps. Units such as batches, series, products, packaging, or shipping units require distinct identification, as do all participants, including companies and relevant operating units, with their physical and electronic addresses. A global location number is utilized to uniquely identify locations, allowing all participating companies and sites, such as processing stations and storage locations, to be recognized within the traceability system. Predefined access keys, such as an article number with batch identification or a serial number, are used to identify units. These keys provide access to relevant data, enabling products to be tracked along the supply and value chain. Typically, a unit comprises products that have undergone the same transformation process, such as batches. When a unit undergoes a transformation, such as through a production process, a new access key must be assigned to reflect the change. (WEGNER-HAMBLOCH & SPRINGOB 2004, p. 61 f.)

Data recording: It is crucial to define the data that needs to be captured and recorded by the traceability system at each phase of the transformation process. Once collected, this data must be securely stored and archived, typically in databases, to ensure it can be quickly and accurately retrieved using the appropriate access keys. Recording, documenting, and archiving relevant data at the outgoing goods department of the supplying company and the incoming goods department of the receiving company are essential steps to maintain product traceability. (WEGNER-HAMBLOCH & SPRINGOB 2004, pp. 63–65)

Data linkage: The linkage between traceability data and products is critical for ensuring a consistent and seamless traceability system, as the weakest link ultimately determines the overall quality of traceability across the supply and value chain. Data captured and recorded within a traceability system can be directly associated with the identification of a series or batch, as well as with corresponding order numbers, timestamps, or other relevant information. (WEGNER-HAMBLOCH & SPRINGOB 2004, pp. 65–67)

Communication: The clearly identified, captured, recorded, and subsequently linked data must be communicated to the respective downstream partners in the supply and value chain. This exchange of information among all participants is essential for an effective traceability system. By referencing the respective access keys of the goods and using standardized data transmission protocols, the connection between the flow of goods and information is significantly streamlined. This enables companies to determine at any time which products have been delivered, processed, or shipped. Depending on the relevance of the data, not all production details need to be shared with the next partner, but completeness and consistency of data within each individual partner's system must be ensured. Additionally, continuous communication throughout the supply and value chain ensures the integration of data with the information flow, maintaining traceability across all stages. (WEGNER-HAMBLOCH & SPRINGOB 2004, p. 69 f.)

2.3.3 Identification and Coding Systems

Optical character recognition

Optical character recognition (OCR) is a technology that enables the conversion of printed or handwritten text from physical documents, such as scanned paper documents, portable document formats, or photos, into machine-readable text (THORAT ET AL. 2022). OCR analyzes the image data, recognizes patterns, and interprets them as characters, words, and sentences (SAHU & SONKUSARE 2017, VAMVAKAS ET AL. 2008). This enables the digital searching, editing, and storage of document content. OCR is used in traceability systems to automatically capture and process product information, such as serial and batch numbers, expiration dates, and delivery data. This streamlines automated data entry, inventory management, and quality control. Additionally, OCR facilitates the efficient processing of delivery documents and supports recall actions by quickly identifying affected products. As a result, it enhances efficiency, improves data accuracy, and strengthens tracking throughout the entire product lifecycle. (CHRISTY ET AL. 2018)

Barcodes

Barcodes are visual representations of data that can be read by machines. They usually consist of a series of parallel lines and spaces of different widths that encode specific information (REINING ET AL. 2019, p. 5 f.). Originally developed to improve product identification in supermarkets, barcodes are now widely used in industries such as retail, logistics, healthcare, and manufacturing (HONG-YING 2009, WYLD 2006). Barcodes are differentiated into one-dimensional (1D) and two-dimensional (2D) codes. The difference between 1D barcodes and 2D barcodes is the amount of data that can be stored.

1D barcodes, also known as linear barcodes, are a type of barcode that represent data by varying the widths and spacings of parallel lines. These lines are typically black on a white background. Each combination of lines and spaces encodes specific information, such as product details, or serial numbers. (FRÖSCHLE ET AL. 2009)

Since 2D barcodes can store data in both the horizontal and vertical dimensions, they are capable of storing over 100 times more data per unit area than 1D barcodes (MOSS ET AL. 2013). 2D codes offer compact storage for large amounts of information, which is useful when marking space is limited. The codes consist of dark squares and light squares arranged in a square or rectangular pattern. These so-called *modules* are the individual small units or cells that form the structure of the code, representing the encoded data. Each *module* can be either dark or light, and their arrangement and size are crucial for the readability of the codes by scanners. The *cell size* refers to the size of the individual modules or squares that make up the code. The size of the cells is typically measured in units such as millimeters or pixels, depending on whether the code is printed on a physical object or digitally displayed. Two widely used 2D codes are Data Matrix codes (DMC) and Quick Response (QR) codes. Their fast readability enables quick data capture and processing using code readers or smartphones. These codes are durable enough to be printed or engraved on various surfaces, allowing them to withstand production and logistics processes. (Youssef & Salem 2007)

For the direct comparison of 1D and 2D codes, the content “TUM iwb” was converted into a barcode according to ISO 8859-1, a DMC, and a QR code. The module size was set to 1 mm for all codes to ensure direct comparability. The codes are shown in Figure 9 .

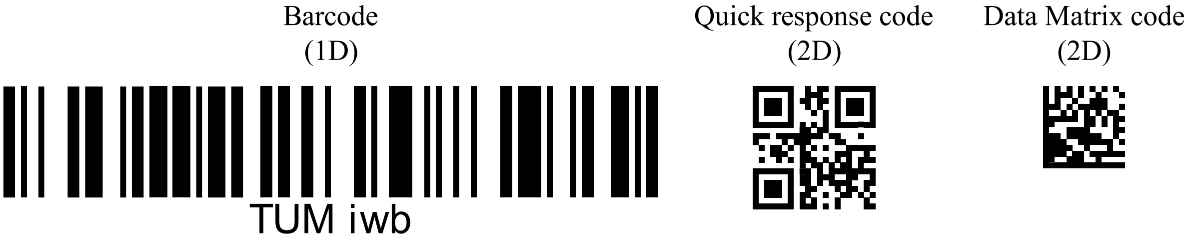

Figure 9: Direct comparison of a 1D barcode and the 2D DMC and QR code, containing “TUM iwb”; the module size is 1 mm for all codes. The codes can be read out using a scanner or a camera of a mobile phone.

Radio-Frequency Identification

Radio-frequency identification (RFID) is a technology that enables wireless data transmission via radio waves between an RFID tag or transponder and a reader (Want 2006b, p. 1 f.). These tags can be attached to or integrated into objects, containing information that can be retrieved by a reader without requiring direct line of sight (Kumar et al. 2009). RFID finds application in various fields, from inventory tracking and logistics to access control (Sarac et al. 2010) and contactless payment (Blass et al. 2009). It provides an efficient means of capturing and processing large amounts of data (Kubáňová et al. 2022). However, despite its benefits, concerns about privacy have arisen due to the potential for capturing sensitive information about individuals or objects (Blass et al. 2009). Advancements in identification technologies, including RFID, have revolutionized the management of raw materials and finished products in the food industry (Kumari et al. 2015). Unlike traditional barcodes, which rely on direct line of sight, RFID offers a more versatile solution by enabling remote identification. RFID tags can store additional data and environmental factors, while RFID readers can autonomously differentiate between multiple tags (Want 2006a).

2.3.4 Theoretical Cost Savings through a Traceability System

Traceability systems are implemented to ensure clarity and transparency in processes, helping to prevent errors and reduce costs. A theoretical, qualitative framework exists for estimating potential cost savings: implementing traceability systems can significantly reduce two major cost drivers in manufacturing: poor-quality products and process costs. By integrating process and quality data, traceability systems improve product quality and facilitate process modeling, enabling the optimization of both product quality and overall equipment effectiveness (OEE). Furthermore, these systems enable more targeted and efficient recall campaigns when necessary. Figure 10 illustrates the cost saving potential associated with applied traceability systems, depending on the traceability granularity, which ranges from batch-level to single-piece tracking. (Buss et al. 2022)

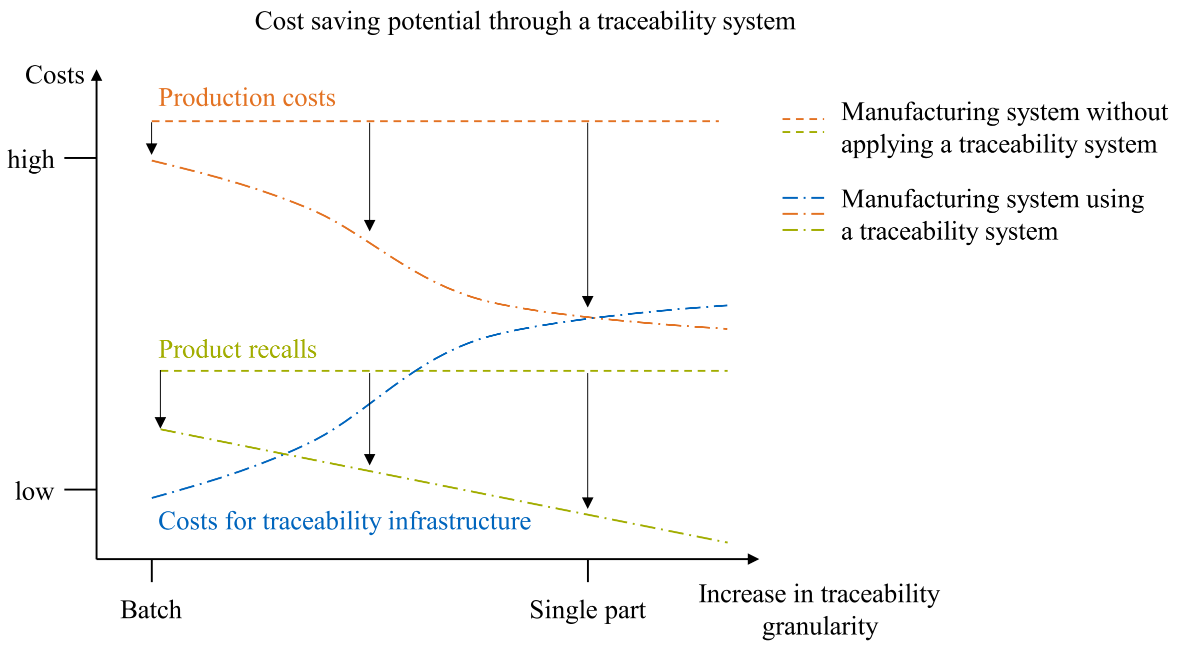

Figure 10: Costs saving potential in a manufacturing systems, product recalls, and traceability infrastructure based on the traceability granularity; adapted from BUSS ET AL. (2022).

It is shown that production costs as well as recall costs can be reduced using a traceability system with increasing granularity. However, the costs for the traceability infrastructure rise. Simply recording data for individual parts does not lead to immediate cost savings. Significant savings are achieved when the production data is used to generate and apply process knowledge, which helps optimize manufacturing. The more granular the data and the insights derived from it, the greater the potential for optimization. This principle also applies to product recalls: a more granular traceability system allows production defects to be traced back to specific intermediate products, facilitating efficient resolution. Other affected products can also be identified more accurately. Nevertheless, infrastructure costs rise with greater granularity, as the effort required for *identification*, *data recording*, *data linkage*, and *communication* for each single part increases. If granularity exceeds a certain level, the resulting infrastructure costs can outweigh the potential savings, making the traceability system economically unfeasible. (BUSS ET AL. 2022)

2.3.5 Applications and Use Cases of Traceability Systems

Traceability systems are already being utilized in various industries, showcasing their effective potential to ensure quality and safety, as well as to meet compliance requirements for legal regulations. Four prominent industries where traceability systems are already well advanced and commonly used are the food industry, the automotive industry, the pharmaceutical industry, and the aviation industry.

Food Industry

Traceability is a cornerstone in the food industry, encompassing every stage from the raw ingredients to the final product (RINGSBERG 2014). Should the need arise to recall food items for any reason, companies possess the capability to pinpoint with precision the specific batches affected by the issue. This ability ensures that potentially hazardous products can swiftly be withdrawn from circulation, safeguarding consumers. Moreover, having detailed knowledge of the exact origin and processing procedures empowers manufacturers to derive effective improvement strategies, thereby elevating the long-term quality standards of food production. (OLSEN & BORIT 2018, BERTOLINI ET AL. 2006)

Automotive Industry

In the automotive industry, the safety of vehicles and their occupants takes center stage for manufacturing companies (KÖNIGS ET AL. 2012). Hence, the stringent requirements regarding traceability. Identifying faulty vehicle parts and associated safety issues in a timely manner is crucial to prevent accidents. Furthermore, regular quality controls are significant to ensure the reliability of vehicles and maintain customer satisfaction. Additionally, adherence to standards and environmental regulations can be demonstrated through this process. (MARO ET AL. 2016)

Pharmaceutical Industry

Traceability is equally vital for companies in the pharmaceutical industry. This sector is subject to strict regulatory requirements, adherence to quality standards is imperative (CHIACCHIO ET AL. 2020). Safety is also paramount here. Through the traceability of pharmaceuticals, recalls can be swiftly initiated, and patients informed. Moreover, the authenticity and origin of medications can be traced through comprehensive documentation, and counterfeits can be removed from the market using traceability systems. The precise documentation enables a comparison between recorded information and expected data, allowing distributors, pharmacies, and other stakeholders to verify the authenticity of medications. ((CHIACCHIO ET AL. 2020, HAJI ET AL. 2021, LEAL ET AL. 2021)

Aviation Industry

In the aviation industry, traceability plays a crucial role in ensuring safety, quality, and reliability. Due to the complex nature of aircraft and their components, it is vital to meticulously track every step in the production and maintenance processes (HO ET AL. 2021). Traceability enables the tracing of the origin of every part of an aircraft, from the smallest screw to the largest assemblies. This approach ensures that the materials used comply with stringent aviation standards and to identify potential safety risks early on. Furthermore, accurate documentation and traceability support maintenance processes by facilitating the swift identification of parts that need replacement or servicing. Overall, traceability is indispensable in the aviation industry to ensure the safety and efficiency of aircraft fleets and to support the seamless operation of airlines worldwide. (SCHREIBER ET AL. 2023, NGAI ET AL. 2007)

3 State of the Art

3.1 Chapter Outline

This chapter focuses on the current challenges in battery production, such as production fluctuations, high scrap rates, and material inefficiencies. It delves into the complexities involved in achieving consistent quality and emphasizes the potential of advanced technologies to address these issues. Data-driven approaches, including machine learning (ML) and real-time monitoring, are introduced as effective strategies for optimizing processes, improving quality control, and reducing costs. Additionally, the chapter examines traceability systems applied to battery cell production, highlighting their importance in creating a comprehensive and reliable data foundation to support these data-driven solutions.

3.2 Current Challenges in Battery Cell Production

The production of LIBs faces numerous challenges, ranging from scaling production capacities and procuring expensive materials to mastering complex production processes (KWADE ET AL. 2018). The following section examines challenges that are directly or indirectly related to production technology.

The combination of the increasing demand for green mobility, renewable energy, and portable electronics is driving the growth of the LIB market and constantly opening new applications for these versatile energy storage devices. To meet the global demand for LIBs, correspondingly high production capacities are required. A study shows that 4 to 12 TWh of batteries will be required per year by 2050 for the electrification of road transportation (USAI ET AL. 2022). This scaling of production requires considerable investment in new factories and production lines as well as the expansion of existing facilities (MAULER ET AL. 2021b). A key challenge in the production of LIBs is the high cost of the raw materials (MAULER ET AL. 2021a). Lithium, cobalt, nickel, and graphite are raw materials that are required in large quantities and high quality. The procurement of these materials poses a challenge, as dependencies on global supply networks arise and limited availability can lead to bottlenecks. In addition, there are ecological and ethnic concerns regarding the extraction and processing of these raw materials. (MANJONG ET AL. 2024)

To achieve consistent high quality in battery cells, the interplay between continuous and discrete processes, as well as the numerous individual steps, must be precisely coordinated (SHARMILI ET AL. 2023). Electrode manufacturing in battery cell production faces several challenges, including the precise control of material mixing and deposition as well as ensuring an even distribution of active materials in the electrode. All materials require precise metering and strict processes due to their significant influence on quality. Production errors in slurry mixing are irreversible and lead to the immediate loss of the batch. Coating and drying demand precise parameters to achieve uniform coating thickness and high electrochemical performance of the electrodes. Additionally, all materials used, such as electrode slurry and current collector foils, must be free from impurities. (LI ET AL. 2022) Small variations in the purity or composition of raw materials can have a significant impact on the performance of the finished battery cells (CHEN ET AL. 2010). In the calendering process, failure modes are differentiated between microscopic and macroscopic defects. Microscopic defects include particle deformation or breakage, while macroscopic defects comprise wavy coating or foil embossing, delamination, and coating cracks (GÜNTHER ET AL. 2020).

Cell assembly demands the precise alignment and connection of individual cell components, requiring highly accurate machines and processes. Every step, from electrode placement to cell sealing, must be executed without errors, as even minor deviations can compromise battery performance and safety. Moreover, the assembly processes must occur under strictly controlled conditions to prevent contamination and material defects. (KWADE ET AL. 2018) One challenge in cell finalization is the precise execution of the electrolyte filling and the sealing processes. This step must be performed under strictly controlled conditions to ensure there are no leaks and that the electrolyte quantity is precisely dosed. (SAUTER ET AL. 2020) Any deviations or errors in this phase can significantly affect the battery quality and lead to failures or safety risks. Precise machines, thorough quality controls and careful management of production conditions are therefore essential. (WOOD ET AL. 2019)

Despite the necessary control and advanced technology in every step of the battery cell production process, numerous cause-and-effect relationships remain unclear. These unrecognized factors lead to production fluctuations, and even small deviations can ultimately result in high scrap rates. These variations are often the result of complex interactions between different process parameters, material properties, and environmental conditions. (BOCKHOLT ET AL. 2016) Each stage of the manufacturing process can be affected by variabilities, such as deviations in the coating thickness, uneven drying of electrodes or variations in electrolyte filling. These variabilities are often difficult to predict and can affect the overall performance and reliability of the battery cells. (WESTPHAL ET AL. 2015) This lack of knowledge makes it difficult to determine appropriate processes parameters and thus minimize costly scrap (ORANGI ET AL. 2024, KEHRER ET AL. 2021).

Production fluctuations can lead to inhomogeneities in the manufactured battery cells (BECK ET AL. 2021). Such inhomogeneities affect the performance and service life of the battery cells and, in extreme cases, can lead to safety risks (RUMPF ET AL. 2018). Therefore, various measurements are taken during production to monitor the quality of intermediate products. These include the continuous monitoring and analysis of production processes, the use of advanced measurement techniques, and the implementation of feedback loops to correct deviations immediately (KORNAS 2021). Modern factories are increasingly relying on automation and digital technologies to improve process control (AICHELE ET AL. 2022). Despite all the quality measures taken in production, not all inhomogeneities can be eliminated. As a result, cells from different production batches, as well as cells made one after another in the same batch, are not perfectly identical (ZHOU ET AL. 2017). However, cells from the same batch generally have less variation compared to those from different batches (SCHINDLER ET AL. 2021). When cells are connected in battery packs, differences in their capacity, self-discharge rates, or CE can cause the battery pack to age faster and thus, to lose usable capacity more quickly (BAUMANN ET AL. 2018).

Furthermore, it has been shown that battery manufacturers often modify their production processes and electrode compositions over time (SCHINDLER ET AL. 2021). Initially, manufacturers might use conservative methods to ensure product specifications are met, but later they may optimize the process to reduce costs and use fewer raw materials, as evidenced by changes in silicon and nickel content (ANK ET AL. 2023a). These adjustments are usually not communicated to customers, who typically receive only basic data sheets. This leads to further challenges in the application of LIBs. The modifications can have significant effects, such as necessitating updates to BMSs or introducing active cell balancing in battery packs that previously did not need it due to tighter tolerances (ZILBERMAN ET AL. 2020). BMSs therefore play a crucial role in the operation of batteries, such as in EVs, by compensating for and balancing fluctuations in the individual battery cells. They ensure that the cells operate within optimal parameters, helping to maintain overall performance and extend the lifespan of the battery. These systems continuously monitor the condition of each cell and compensate for differences in cell performance through targeted control of charging and discharging processes. (GABBAR ET AL. 2021)

The growing demand for LIBs requires high production capacities and significant investments. However, challenges in battery production arise from the high cost of raw materials, the need for precise coordination in manufacturing processes, and the difficulty in understanding the complex cause-and-effect relationships that lead to production fluctuations and high scrap rates. To address these challenges, data-driven approaches are employed in battery production to reduce fluctuations and scrap. These approaches enable more precise monitoring and analysis of process parameters, allowing for early detection of patterns and deviations before they result in quality issues or scrap. By continuously capturing and evaluating production data, real-time process optimization is achieved, leading to more stable production and significant reductions in scrap rates.

3.3 Data-Based Applications for Quality Assurance and Process Understanding

SCHNELL & REINHART (2016) addressed the need for an effective quality management in battery manufacturing and proposed a quality assurance concept. This concept introduced a systematic approach in which production processes were divided into stages, each with specific quality gates that must be passed before the next stage is reached. This method was designed to identify defects at an early stage to ensure that only products that meet strict quality standards pass through the production line. Furthermore, the publication emphasizes that a large and sufficient data basis is essential to support and back this approach. (SCHNELL & REINHART 2016)

SCHNELL ET AL. (2019) presented data mining methods applied to LIB cell production to uncover unknown cause-and-effect relationships. Data collected during numerous production ramp-ups in a research facility were processed using the cross-industry standard process for data mining (CRISP-DM) to define data mining goals and select appropriate algorithms. Different algorithms were used to predict the cell capacity, revealing that electrode manufacturing, the mass of the cell before electrolyte filling, and the amount of electrolyte had significant effects on the cell capacity. The study demonstrated that data mining methods were successfully used to identify process parameters influencing product quality in real production settings. Challenges included obtaining sufficiently large and high-quality data sets and integrating comprehensive tracking measures. The findings indicated that these methods could help forecast intermediate product attributes. (SCHNELL ET AL. 2019)

THIEDE ET AL. (2019) investigated the use of data mining techniques to improve quality prediction in battery production. The main objective was to develop methods for predicting the battery quality by analyzing various factors that influence the production to enable better control and optimization. To achieve this, a range of data mining techniques, including ML algorithms and statistical methods to analyze data collected throughout the production chain were used. A significant focus was placed on multi-criteria quality prediction, recognizing that battery performance is influenced by a complex interplay of various parameters. As a result, critical factors impacting the final product quality were identified. By understanding these factors, the study aimed to improve quality prediction, leading to higher efficiency, reduced production costs, and fewer defects. This, in turn, enhanced the reliability and performance of battery cells. Additionally, the publication discussed practical strategies for integrating data mining tools into existing production systems, addressing potential challenges and proposing solutions. (THIEDE ET AL. 2019)

TURETSKYY ET AL. (2020a) focused on enhancing quality control in the production of LIB cells using advanced data-driven techniques. The aim of the study was to optimize the quality inspection process in battery production by integrating a data-driven cyber-physical system. This system utilized real-time data and advanced analytics to improve quality control points along the production process. The authors proposed a framework that combines physical manufacturing systems with cyber-technical capabilities. This involved capturing data from different stages of production and analyzing it to detect and address potential quality issues early before they can affect the final product. The methodology described the implementation of this system using sensors and data analytics. It explained how data from manufacturing equipment and processes were analyzed to inform quality control decisions and improve production efficiency. The results showed that the integration of this data-driven system enabled significant improvements in the early detection of defects. (TURETSKYY ET AL. 2020a)

TURETSKYY ET AL. (2020b) explored how data-driven methodologies could significantly enhance the production and quality control processes in LIB manufacturing. The authors addressed industry challenges such as the need for improved efficiency, quality control, and cost reduction. It introduced the concept of data-driven manufacturing, utilizing data analytics and real-time monitoring to tackle these issues and drive improvements. A key focus was on comprehensive data collection across various stages of battery cell production, including material preparation, cell assembly, and testing. The integration of data from diverse sources like sensors and production equipment was emphasized, aiming to provide a holistic view of the manufacturing process. Several applications of data analytics, including quality control, process optimization, and predictive maintenance, were discussed. ML algorithms were highlighted for their ability to predict defects, optimize production parameters, and foresee equipment failures. The role of real-time monitoring systems in providing immediate feedback on production quality and process conditions was examined. Continuous monitoring allowed for dynamic adjustments to manufacturing processes. The challenges of data-driven approaches were discussed, including difficulties with data integration, the need for advanced analytics infrastructure, and cybersecurity concerns. It emphasized the importance of having skilled personnel capable of analyzing the production data and implementing practical improvements as an additional challenge. (TURETSKYY ET AL. 2020b)

WESSEL ET AL. (2020) emphasized the integration of traceability systems within battery production. The research highlighted the importance of tracking and tracing systems in enhancing data mining applications. It was found that the implementation of these systems facilitates the collection of comprehensive data, which can be used to improve quality control and process efficiency. This integration allows for better prediction and identification of key factors affecting battery performance. (WESSEL ET AL. 2020)

TURETSKYY ET AL. (2021) dealt with the optimization of battery production processes through advanced ML techniques. The authors proposed using multi-output ML models to simultaneously predict the efficiency and the cycle life. By integrating these models, manufacturers could design batteries that meet multiple criteria and improve their overall production efficiency. The approach helped to identify optimal production configurations and materials. This work emphasized the benefits of data-based methods in improving design decisions and streamlining the manufacturing process. (TURETSKYY ET AL. 2021)

ZANOTTO ET AL. (2022) examined the crucial role of data specifications in the digital transformation of battery manufacturing. The authors provided an overview of the current state of digitalization within the industry, focusing on the importance of effective data management. This work reviewed state-of-the-art practices and technologies used for data management in battery production, highlighting advancements in digital solutions and data collection. Additionally, several challenges, such as inconsistent data formats and interoperability issues between different systems and stakeholders, were identified. These challenges hindered the effective integration and utilization of data across various stages of production. The publication pointed out opportunities for improvement. Developing standardized data formats and protocols was suggested as a way to significantly enhance integration, communication, and data sharing across the industry. (ZANOTTO ET AL. 2022)

HENSCHEL ET AL. (2023) explained the use of a digital twin technology in battery production. Digital twins are virtual models that replicate physical plants, processes, or systems and enable real-time monitoring, analysis, and optimization. In this publication, the digital twin was a digital representation of a physical object that provides insights into its performance, status, and behavior. Several applications of digital twins in battery manufacturing were presented in this publication. Digital twins can be used for process optimization to simulate and refine manufacturing processes to increase efficiency and minimize scrap. The authors supported predictive maintenance by monitoring equipment performance and predicting maintenance needs, which can prevent unexpected breakdowns in production. In quality control, digital twins enabled real-time monitoring and control to ensure that battery cells meet the required specifications. The authors facilitated the virtual testing and validation of new battery developments and designs. (HENSCHEL ET AL. 2023)

KIES ET AL. (2023a) presented a comprehensive strategy for integrating digital technologies into the quality assurance processes of battery cell manufacturing. It outlined how digital tools had enhanced the accuracy, efficiency, and reliability of quality control throughout the production cycle. The publication highlighted the need for a holistic approach that combined various digital technologies, such as data analytics, ML, and real-time monitoring systems, to manage and improve quality assurance in battery cell production. By integrating these technologies, manufacturers were able to achieve better oversight of production processes, identify and address quality issues more effectively, and ensure consistent product quality. The publication discussed the benefits of using digital systems to collect and analyze data from different stages of production. This approach allowed for more precise tracking of production parameters, improved detection of anomalies, and the ability to make data-driven decisions that enhanced overall production quality. They additionally addressed the challenges associated with implementing digital quality assurance systems, such as the need for significant investment in technology, the integration of new systems with existing production processes, and ensuring the security and reliability of data. (KIES ET AL. 2023a)

Further work investigated the application of ML in the production of LIB cells, with a particular focus on the manufacture of electrodes. A data-driven method was enabled by ML to model the relationship between intermediate product properties and process parameters for individual electrode production sub-processes (TAN ET AL. 2023). For example, the influence of slurry structure was studied by examining its physical and rheological properties and their impact on the final characteristics of an electrode. Because quantifying the effects of numerous interconnected control variables on the electrode was difficult with traditional trial-and-error methods, an explainable ML methodology and a systematic statistical analysis method were proposed to enable comprehensive assessments. (NIRI ET AL. 2022c)

Furthermore, the use of ML techniques was emphasized to optimize various aspects of battery production, including quality control, process efficiency, and cost reduction. A comprehensive overview of various ML techniques was provided that have been applied in the production of LIB cells. It highlighted how these techniques have supported to improve production processes, increase product quality, and reduce costs (HAGHI ET AL. 2023). A second work focused on combining design of experiments with explainable ML to analyze the dependencies in electrode manufacturing. This combined approach enabled a more efficient and transparent analysis of the impact of different factors on the performance and production results of the electrodes (HAGHI ET AL. 2024a). A third work examined the complex interdependencies in electrode manufacturing. Design moment extensions and explainable ML methods were used to understand

and optimize these relationships, improving the overall productivity and effectiveness of the manufacturing process (HAGHI ET AL. 2024b).

Other data-driven approaches have already used ML to make statements about the final cell performance. The application of interpretable ML models was used to predict battery capacities and analyze the impact of coating parameters. Different models, such as decision trees and random forest, were applied to accurately predict battery capacities and identified key influencing factors (LIU ET AL. 2022). Another study focused on advanced ML to demonstrate that these approaches can effectively optimize manufacturing parameters, resulting in a cleaner and more efficient cell production. Critical dependencies between electrode characteristics and cell performance were revealed, providing deeper insights into how electrode design influences battery performance (NIRI ET AL. 2021, NIRI ET AL. 2022b)

Data-driven approaches have been used to explore the interaction between various intermediate products in a battery cell. The negative to positive (N/P) ratio refers to the proportion of anode (negative electrode) material to cathode (positive electrode) material in the cell, which significantly impacts the battery's capacity, energy density, and overall performance. Achieving an optimal N/P ratio ensures efficient use of materials, maximizing energy storage and delivery while maintaining stability. A high ratio of anode material can cause inefficiency, while too much cathode material leads to underutilization. ML algorithms have been applied to investigate the effect of the N/P ratio on cell performance. The results indicated that performance at different C-rates was influenced by various factors, with the N/P ratio having a smaller impact on electrochemical performance compared to other factors such as electrode thickness, active material mass loading, and cathode areal capacity. Furthermore, the dependencies of these factors were found to be unique for each C-rate, with both linear and non-linear relationships observed. (NIRI ET AL. 2022a)

The literature outlines a range of data-driven approaches designed to identify and understand previously unknown cause-and-effect relationships within battery production processes. However, a consistent and sufficiently large data foundation is a key prerequisite for the success of these approaches. Without such a data foundation, the complex interactions between process parameters and product quality cannot be reliably analyzed. An effective way to obtain consistent datasets from individual process steps is the use of traceability systems. These systems enable seamless tracking of materials and processes, thereby creating a structured and comprehensive data basis. Data-driven approaches can only reach their full potential when supported by a sufficiently large and high-quality data foundation.

3.4 Traceability Concepts in Battery Cell Production

RIEXINGER ET AL. (2020) developed a traceability concept focused on identification technologies. The concept was morphologically evaluated for each process cluster and trace object within battery production. The authors identified different implementation strategies to eliminate information gaps between processes, such as the electrode production (coating, calendering, cutting) and the cell assembly. One possibility was to mark the current collector foils with ink markings. Further tests and long-term studies were deemed necessary to avoid potential negative effects of the applied identifiers on cell quality, such as particle entry from labeling ink. However, direct tracing and serialization methods, such as using the surface micro-structures of the electrode foil, did not require this as they left no traces or particles on the electrode. The solution described in the morphological analysis needed to be combined to form a consistent implementation and information link. This would enable tracing individual components and process steps of the final battery, as well as connecting information from previous processes at the cell level. Eliminating identification and information gaps between process clusters would enable the traceability of battery components and process steps up to the finished product in current and future battery production systems. (RIEXINGER ET AL. 2020)

WESSEL ET AL. (2021) investigated an ontology-based approach to enhance the data acquisition and the interoperability in battery cell manufacturing. They found that conventional data management methods were inadequate for ensuring smooth integration and communication between different production systems. The theoretical concept proposed a traceability system that used ontologies, formal structures defining relevant relationships and concepts in battery cell production. This system aimed to standardize data representation and improve the integration and sharing of information across various production tools and stages. The design of the system involved creating a unified framework for collecting and organizing battery production data. This framework enabled real-time monitoring and ensured accurate traceability by aligning data from different sources into a cohesive format. The ontology-based system offered several benefits, including improved data interoperability for better communication between disparate systems and enhanced traceability for more effective quality control and operational efficiency. (WESSEL ET AL. 2021)

WESSEL ET AL. (2023) conducted a study on the role and implementation of traceability systems in battery cell production. They analyzed how systematic tracking and documentation improved quality control and product reliability, highlighting the crucial role of traceability in meeting the high standards of battery production. It was highlighted that effective traceability systems are crucial for managing the diverse and complex production processes, including the raw material sourcing, the cell assembly, and the final product testing. Key aspects of traceability detailed in the publication included the use of unique product identifiers, such as serial numbers or barcodes, for each battery cell. These identifiers allowed for precise tracking of individual cells throughout their entire lifecycle, from production to end-use. The study also discussed the importance of collecting detailed data at various stages of production, including material sources, production parameters, and quality control tests. Effective data management systems were deemed necessary for aggregating and analyzing this information to monitor product quality and identify potential issues. The integration of advanced technologies, such as real-time monitoring systems and data analytics, was examined as well. These technologies facilitated continuous tracking of production processes and helped detect anomalies or deviations from quality standards. This capability was essential for addressing quality problems quickly and effectively, thus reducing the risk of defective products reaching the market. Additionally, the publication highlighted that traceability was important not only for internal quality control but also for meeting regulatory requirements. Compliance with industry standards often required detailed records and product traceability. Challenges like integration, data accuracy, and costs were addressed with solutions such as standardized protocols and scalable data management technologies. (WESSEL ET AL. 2023)

KIES ET AL. (2023b) theoretically explored methods to enhance traceability in battery cell production, emphasizing the importance of assigning unique identifiers, such as serial numbers or QR codes, to each battery cell. These identifiers facilitate tracking throughout manufacturing and the supply chain. The study discussed how integrating data from different production stages could improve quality monitoring, ensure compliance, and enable efficient recalls when necessary. It also addressed theoretical challenges, such as integrating new traceability systems with existing technologies, securing data, and scaling solutions to accommodate various production capacities. (KIES ET AL. 2023b)

SCHOO ET AL. (2023) addressed the challenges associated with detecting and tracking coating defects in LIB electrodes during production. The authors highlighted that the importance of coating quality in LIB electrodes. This work reviewed various types of coating defects, such as non-uniformity, cracks, and delamination, and their potential effects on battery efficiency and safety. The publication examined inline detection methods used to identify these defects during the manufacturing process. The study explored advanced technologies and methods designed to identify and evaluate coating defects in real time. Key innovations included optical inspection systems, machine learning algorithms, and advanced imaging techniques. These tools enable precise defect detection, automated analysis, and immediate feedback during the coating process, ensuring consistent quality and reducing the likelihood of production errors. Additionally, the study examined methods for tracking defects throughout the entire battery production line. Effective tracking systems were deemed crucial for ensuring that defective products were identified and addressed promptly. In summary, the publication emphasized the benefits of implementing robust inline detection and tracking systems for coating defects. (SCHOO ET AL. 2023)

RIEXINGER ET AL. (2023) covered a novel method for ensuring traceability in battery production. Tracking and identifying individual electrode segments within battery cells was mentioned as an important aspect to improve quality control and performance monitoring throughout the battery life cycle. Traditional identification methods often rely on physical markings or labels, which are inherently prone to human error and inefficiency. These methods can be cumbersome, especially in complex manufacturing processes, where maintaining accuracy and consistency in marking, reading, and tracking is challenging. The method proposed in the publication eliminates the need for physical markings by using advanced imaging and data analysis techniques. This marker-free identification system allowed precise tracking of electrode segments without altering the physical structure of the battery. The system used high-resolution imaging and ML algorithms to recognize and record the unique characteristics of each electrode segment. Key benefits of this new approach included increased accuracy in tracking electrode segments, resulting in better quality control, reduced risk of errors associated with physical markings, and improved efficiency in the battery production process. (RIEXINGER ET AL. 2023)

OTTE ET AL. (2024) concentrated on identifying crucial parameters for effective traceability during the continuous mixing stage of the battery cell manufacturing. The study underscored the importance of traceability in this process, where raw materials are blended to produce electrode materials. The research identified several key parameters that needed to be closely monitored and recorded to achieve effective traceability. These included the properties of raw materials, such as particle size and chemical composition, mixing conditions, including the temperature, the mixing speed, the duration, and the equipment performance, encompassing metrics on the calibration and the operational status. The work highlighted that accurate tracking of these parameters was essential for diagnosing issues. The authors explored various methods and technologies for capturing and managing traced data, such as sensors, data logging systems, and software solutions integrated with manufacturing execution systems. (OTTE ET AL. 2024)

3.5 Conclusion and Need for Action

The growing demand for LIBs, driven by EV adoption, renewable energy storage, and portable electronics, requires significant investments in production capacity while facing challenges like high raw material costs, complex manufacturing, and unknown cause-effect relationships that lead to production inefficiencies and costly scrap. Digitalization and data-driven approaches are increasingly being used to improve process understanding in battery cell production. These are intended to uncover unknown cause-and-effect relationships. The resulting understanding should then be used to design and operate production processes more efficiently and with fewer scrap. Applying these approaches effectively requires consistent and comprehensive production data, but significant gaps in the quality and availability of this data severely limit the methods' potential to reduce scrap. A traceability system can support this by establishing a consistent and comprehensive data foundation.

A holistic traceability system can track and document every step of the production process of a battery cell, from the procurement of raw materials to the delivery of the final product to the customer. Such a system collects and stores vital data at each stage, ensuring complete traceability across the entire process chain. This allows for the materials and processes used at each stage to be traced at any given time. By integrating and linking data from various production processes, machines, and locations, a central database is created, containing comprehensive information. This database enables precise monitoring and quality assurance at each production step, allowing for the quick identification and rectification of deviations and errors. By analyzing production data in detail, processes can be optimized, leading to increased efficiency and reduced scrap. Additionally, in the event of product defects or recalls, the system enables rapid and targeted tracing of affected batches or products, speeding up the recall process and minimizing its impact. Overall, a traceability system provides better control and transparency in production, resulting in higher and more consistent product quality and reduced costs.

Despite the theoretical discussion of traceability concepts in the literature, significant gaps remain in their practical application. While the existing research on traceability systems for LIB production has largely been theoretical and not experimentally validated, a critical gap exists in developing and validating a method for the clear identification of intermediate products across the entire process chain. Accurate identification of intermediate products is essential for properly associating product and process data, but while technical solutions for identifying individual components have been proposed, they have not yet been integrated into existing production lines as viable hardware solutions. Especially in electrode manufacturing, where key product parameters for the final battery cell are defined, the analysis is still primarily conducted at the batch or coil level. The continuous process steps, which are crucial for the final battery performance characteristics, have not been sufficiently differentiated. Although defects can be detected with sensor technology, it remains impossible to trace these defects back to specific intermediate products, which means that entire batches are often classified as scrap due to the inability to localize defects precisely.

While individual process steps and their associated production data have been analyzed in depth in previous studies, a comprehensive and practically implemented traceability system spanning all stages of battery cell manufacturing is still missing. Existing research primarily remains at a conceptual or theoretical level and has not yet demonstrated the feasibility or measurable benefits of such systems in real production environments. In particular, the systematic use of fine-grained, cross-process data to derive deeper process insights and enable data-driven optimization has not been explored to date. Consequently, despite the existence of theoretical traceability frameworks, their end-to-end implementation and validation under industrial conditions remain an open research challenge. Addressing this gap by developing and applying a holistic traceability system with comprehensive data integration constitutes the central novelty and primary motivation of this work.

4 Cumulative Presentation of the Publications

4.1 Chapter Outline

The review of the preliminary scientific work in Chapter 3 identified key gaps in battery manufacturing research, particularly in integrating traceability systems across the entire production process and the validation of theoretical potential. A comprehensive traceability system covering the entire production chain is still missing, and the identification and tracking of intermediate products remains unresolved. This lack of traceability limits defect detection and process optimization.

The doctoral thesis is structured as a compilation of publications. It encompasses six distinct publications (P I–VI) whose contents are summarized the following. This chapter addresses the identified scientific needs and outlines the applied approach. Building upon the current state of the art, it defines the problem statement along with associated scientific objectives (SO). The approach is then detailed, including sub-SOs.

4.2 Scientific Objectives and Approach

Scientific Objectives

The objective of this dissertation is to design, implement, and empirically validate a holistic traceability system across the battery manufacturing process, thereby demonstrating its practical feasibility and its potential to enable fine-grained process transparency and data-driven optimization. Product and process data should be accurately linked to individual intermediate products, enabling their characterization based on the collected data. Therefore, a comprehensive requirements analysis is necessary, considering both the entire process chain and specific steps in battery cell production. A method is essential for identifying intermediate products during production and tracking them through subsequent production steps. Adapting the structure of the production data to account for detectable intermediate products is indispensable. This adaptation ensures the precise linking of data to intermediate products, enhancing their identification and handling on an individual basis. Finally, the allocated data from the traceability system is utilized to identify defective intermediate products and uncover relationships between processes and products. Four specific SOs were derived from the need for action identified in Chapter 3 and are grounded in the state of the art. These objectives are outlined and explained in detail below.

SO 1: **Conceptional design of a traceability system for the battery cell production**

For a traceability system in battery cell production, a comprehensive concept with sufficient data granularity is essential. This level of granularity must enable the tracing of production variations and defects back to all intermediate products, ensuring precise identification. Existing concepts from the state of the art are applied and adapted to meet these requirements, focusing on achieving the necessary resolution for effective defect tracking and process optimization.

SO 2: Identification strategy

A suitable identification strategy for all intermediate products is to be defined, considering the requirements and boundary conditions of the process steps of battery cell production. Challenges for identification possibilities must be identified and addressed.

SO 3: Setup and validation of the overall traceability system

The individual components of the developed traceability system must be aggregated for a comprehensive system. Experimental investigations on traceable product and process parameters have to be carried out. The functionality of the entire traceability system has to be demonstrated.

SO 4: Application of the traceability system

The gained data granularity through the implemented traceability system is utilized to demonstrate how production deviations and errors can be identified and to build a deeper understanding of the process. A fundamental demonstration has to be provided that use of the traceability system allows for effective defect detection and unveiling process product relationships.

Approach

The approach of this dissertation is structured into four main SOs, each with corresponding sub-SOs. For each individual SO, a dedicated publication was produced that scientifically elaborates on and discusses the specific topic, as illustrated in Figure 11.

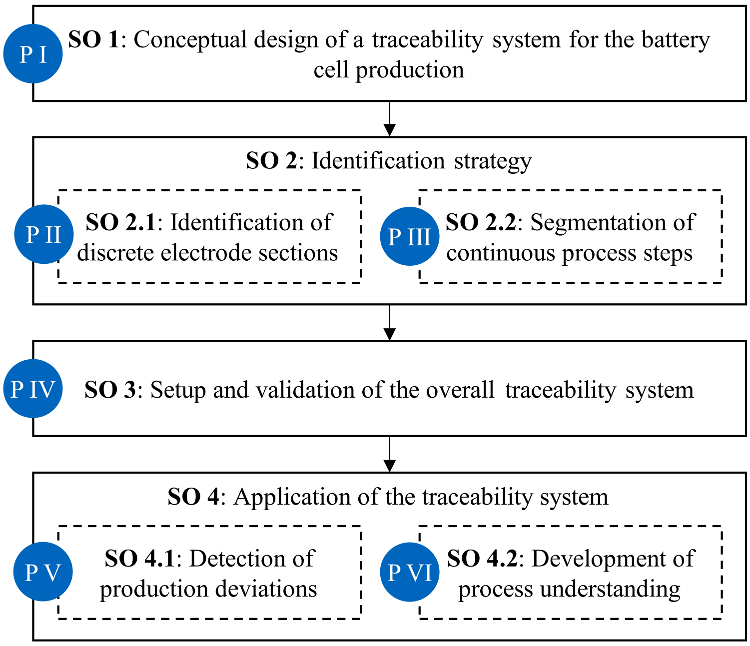

Figure 11: Approach of this dissertation, divided into four main SOs with respective sub-SOs.

The analysis differentiated between cross-process chain requirements and process-specific requirements. Cross-process requirements stemmed from the predefined system boundaries, where it was necessary to determine which areas of battery cell production should be traceable and classify material flows as inputs, intermediate products, or outputs. Once these boundaries were established, the production processes were categorized into individual part, batch, and continuous processes. Existing traceability concepts were adapted for individual part processes. However, specific requirements were also identified for each process step. To achieve this, all individual steps within the entire process chain, as defined by the system boundary, were examined in detail.

The identification of individual intermediate products, particularly in continuous processes, was ensured by conducting an in-depth analysis of suitable identification technologies. These technologies were rigorously evaluated based on their capability to reliably and effectively identify and distinguish individual intermediate products within the production workflow. Based on the findings from the literature, specific identification technologies were selected and experimentally tested. The testing considered the identified boundary conditions to ensure the chosen methods were viable within the specific requirements of the production environment.

After ensuring the identification of all relevant intermediate products with sufficient granularity, the traceability system was implemented across the entire battery production process. Additionally, the data structures for product and process information were aligned with the traceability granularity of the intermediate products. The system's functionality was validated across the process chains using appropriate parameters.

Two use cases enabled by the traceability system were demonstrated, utilizing comprehensive and consistent product and process data. This approach facilitated the detection of production deviations and contributed to the development of a deeper process understanding. It was shown that individual intermediate products could be identified, with their associated production data analyzed. Furthermore, by precisely linking product and process data, the behavior of an electrode was thoroughly characterized within a single process step.

4.3 Publication I: Marking of Electrode Sheets in the Production of Lithium-Ion Cells as an Enabler for Tracking and Tracing

Summary

In this publication, a concept was elaborated for a comprehensive traceability system. The aim was to ensure the traceability of the production of each individual manufactured battery cell. Since every process step in battery cell production affects the final cell properties, all relevant production parameters from mixing to formation must be recorded. Production data consist of the set process parameters and the measured product parameters. By considering the process steps, the boundaries of the traceability system were defined, based on a review of existing literature. The upstream material synthesis and downstream application of the manufactured battery cells were not further considered. Regarding data granularity, the concept defined that the traceability of all intermediate products in battery cell production should be detailed down to the level of a single electrode sheet. This decision was made to ensure that production data can be linked to each individual intermediate product within the manufacturing process, allowing for precise monitoring of potential defects or variances at the most granular level. For the establishment of a traceability system, the individual intermediate products must be identifiable as they represent the later TRU. Concerning the process chain, it was proposed that the electrode slurry represented the first TRU. Due to the nature of the process, only a batch consideration is possible here. The second TRU consisted of individual electrodes. Production data from electrode production must be assigned to individual intermediate products, and not, as previously, at the coil or batch level. The third TRU consisted of the manufactured cells. Once the electrodes have been processed into a cell stack or roll, the production data was assigned to the individual cells. By establishing connections between the cells, the electrodes used within them, and the corresponding slurry, continuous traceability throughout the production process can be achieved. In Figure 12, the schematic process chain of battery cell production, along with the respective intermediate products to be marked, are shown.

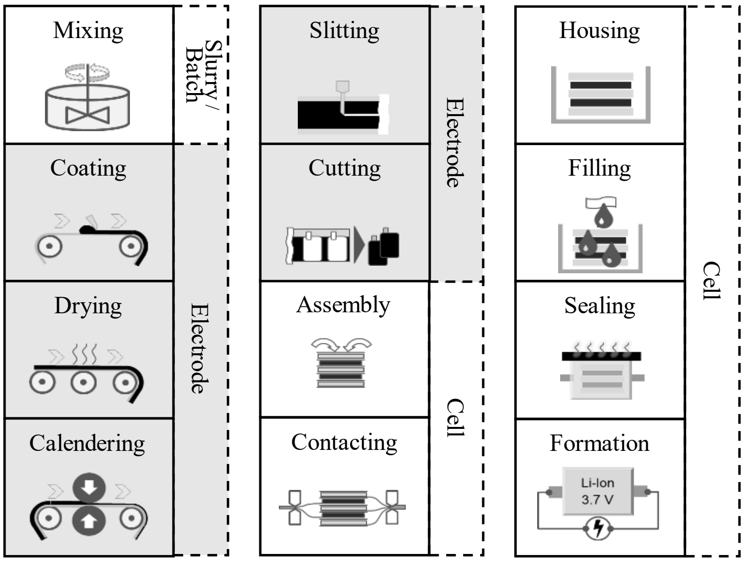

Figure 12: Marking objects for different process steps in the LIB production for the example of pouch cells; figure adapted from SOMMER ET AL. (2021).

To make individual electrodes identifiable during the coating, drying, and calendering process, an identification method was needed. Given the state of technology, physical marking was integrated into the process chain as RFID chips and magnetic stripes were found to be unsuitable due to their quantity requirements, application speed, and inability to withstand battery production conditions. Ink and laser marking systems have been identified as promising marking technologies. These systems have proven effective in other industries and enable clear identification of intermediate and finished products. Thus, this marking allows for the recognition and differentiation of individual electrodes. At relevant process steps or points in electrode manufacturing, these markings can be used for the data assignment of production data.

To introduce a marking into the production of LIB cells, several requirements must be met to ensure it does not negatively impact throughput times or quality. Markings must be chemically stable, thermally resilient, mechanically durable, and geometrically suitable to be successfully integrated into the production process. The marking must be chemically resistant to withstand contact with solvents during the coating process and with electrolytes added later, without dissolving or affecting the electrochemical properties of the manufactured battery cell. It must also endure high temperatures during the drying and calendering processes. Mechanically, the marking needs to withstand high pressure and shear forces during calendering and ultrasonic welding without affecting cell performance or readability. Additionally, the marking must be applied to the current collector tabs of the electrodes in a way that maintains readability after cutting the electrodes and does not interfere with the coating process.

Key Findings

The following key findings (KFs) are derived from the publication of SOMMER ET AL. (2021).

KF 1: A concept for a traceability system was designed for LIB cell production that records all relevant production parameters from mixing to formation. This system must track production data down to individual electrode sheets, with the goal of linking each cell to its components, including the slurry and electrodes, to ensure continuous traceability throughout the process chain.

KF 2: Ink and laser marking technologies are suitable for the traceability application, offering clear and durable identification, which are impractical due to their inability to withstand production conditions and the need for large quantities.

KF 3: Markings for LIB production must be chemically resistant, thermally resilient, and mechanically durable. They must be applied in such a way that they do not impact cell performance or readability, remaining functional after electrode cutting and during processing.

Contribution of the Authors

Alessandro Sommer designed the traceability concept and considered the boundary conditions of battery cell production. Sajedeh Haghi and Matthias Leeb assisted with the literature research. Florian J. Günter and Gunther Reinhart edited the publication.

4.4 Publication II: Integration of Electrode Markings into the Manufacturing Process of Lithium-Ion Battery Cells for Tracking and Tracing Applications

Summary

As described in Chapter 4.3, physical markings are essential for a holistic traceability system in LIB cell production. Ink-based and laser-based markings were selected, as they have proven to be suitable. An example of these markings, including ink-based and laser-based DMCs, along with enlarged modules on copper and aluminum foil, is shown in Figure 13.

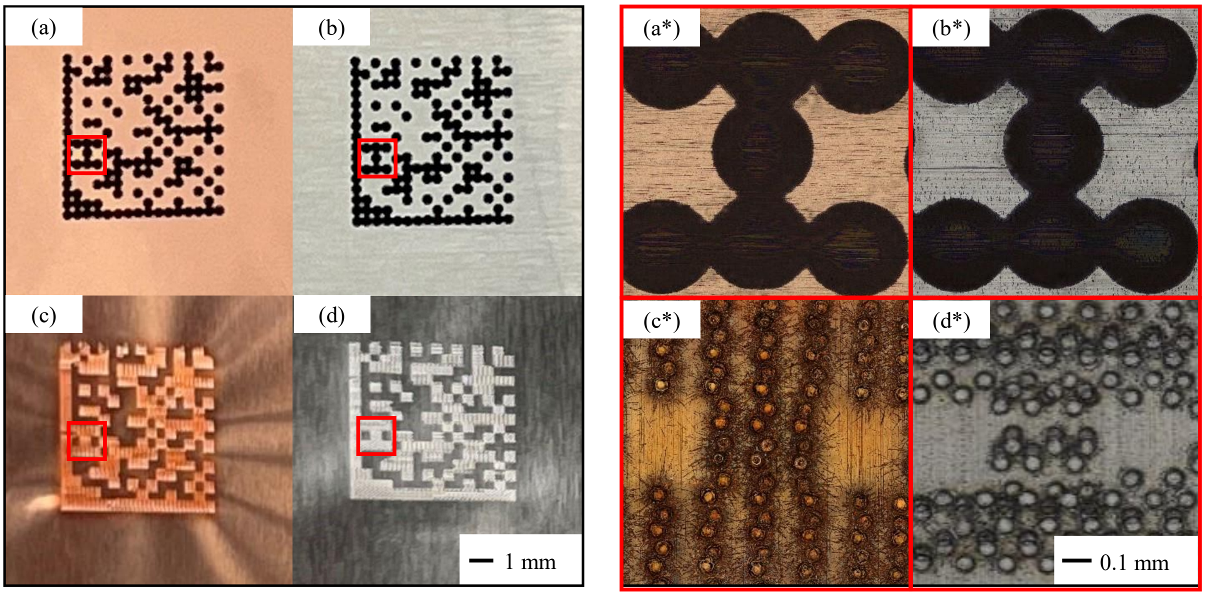

Figure 13: (a) Copper foil with ink-printed DMC, (b) aluminum foil with ink-printed DMC, (c) copper foil with laser-marked DMC, (d) aluminum foil with laser-marked DMC; corresponding enlargements (a*–d*) of the red-outlined modules of the four codes. For a module size of 0.35 mm, the codes had a resulting size of 5.6 × 5.6 mm; figure adapted from SOMMER ET AL. (2023b).

Markings on the foils must remain readable throughout the entire production process to be effectively integrated into a comprehensive tracking and tracing system. To ensure their durability, these markings were tested under various critical conditions derived from the individual process steps in battery production. A methodical approach was proposed in the publication for conducting the experiments, which included the following investigations.

Regarding the geometric constraints defined by the limited space available on the current collector foils, various code formats were examined for their spatial requirements. The DMC emerged as the most efficient encoding format, capable of storing specific information in the smallest possible area. To assess the temperature resistance of laser and ink markings, marked foils were subjected to temperatures of up to 500 °C. While ink codes faded or disappeared at certain temperatures, laser markings demonstrated no susceptibility to heat. To evaluate the chemical compatibility of ink markings and their potential contamination of the electrolyte, coin cells were produced and tested, comparing cells with and without ink contamination in the electrolyte. Subsequently, the cells were subjected to a cycle life testing, and the remaining available capacity was analyzed. No differences were observed between the two groups, though long-term effects of ink markings cannot be ruled out. For the mechanical analysis, foils with laser markings were compared to unmarked foils regarding their maximum tensile strength. It was observed that laser markings caused a notch effect, reducing the maximum tensile strength. This effect was also noted in laser markings within the joining zone between the tab and the current collector foil, where a decrease in tensile strength was similarly observed. However, in both cases, the reduction was not severe enough to hinder further processing of the intermediate products. In contrast, ink markings within the joining zones did not reduce the maximum tensile strength.

Experiments on the *iwb* production line demonstrated that both ink and laser marking systems are suitable. However, each specific production line has unique process environments and thus requirements, so quality assurance steps must be tailored and repeated according to the specific foils, inks, or laser parameters used.

Key Findings

The KFs of the publication of SOMMER ET AL. (2023b) can be consolidated as follows.

KF 1: The study demonstrated that as the amount of code content increased, all code formats required more space. Among the formats tested, the DMC occupied the least space for the same amount of information, making it the most suitable for electrode sheets.

KF 2: The experiment demonstrated that ink-printed codes have a maximum temperature resistance, making them suitable for the thermal conditions in battery cell production. The ink markings withstood the highest thermal stresses of 120 °C encountered in the process chain, confirming their applicability for electrode production.

KF 3: The cycle test revealed no significant impact on cycling resistance for cells with inked electrolytes compared to those without.

KF 4: Laser marking weakened the foils used; however, this did not restrict their processability. Additionally, the use of laser markings contributed to a reduction in the strength of the weld seam between the tabs and the foils.

KF 5: Each production line has unique boundary conditions for ink or laser marking, necessitating tailored quality assurance steps. For specific foils, inks, laser parameters, and code formats, experiments must be adapted and validated, ensuring the marking's compatibility with and resilience to the physical effects of the specific production process.

Contribution of the Authors

Alessandro Sommer designed the procedure for the experiments, conducted them, and analyzed the results. Matthias Leeb and Lukas Weishaeupl assisted with the execution of the experiments and the analysis of the results. Rüdiger Daub edited the publication.

4.5 Publication III: Development and Implementation of Inline Segmentation for Continuous Electrode Production in Lithium-Ion Battery Cell Manufacturing for Traceability Applications

Summary

The publication presented two methods for segmenting electrodes inline during the coating process to enable tracking and tracing of individual electrodes. The authors explored the use of laser and ink marking systems for applying unique, readable markings to assign production data to specific electrode sections. Both systems required integration adjustments based on their operational modes. Laser marking created durable and legible markings by causing physical changes to the substrate surface. This method requires synchronized movement and a constant working distance between the laser and the work piece surface. Safety concepts and particle extraction were also necessary for an inline application. Ink marking involved drop-on-demand (DoD) and continuous inkjet (CIJ) systems. DoD generated droplets in response to digital signals, while CIJ used a modulated continuous liquid stream. Both required a consistent marking distance and regular ink refills, with either the object or the marking head moving in a known pattern to create 2D structures. For both laser and ink marking systems, it was essential to ensure straight and vibration-free foil movement. This could be achieved using the rolls of the coating system or by incorporating additional support rolls. A constant marking distance could be maintained by mechanically coupling the marking heads with the corresponding rolls. Traverse control was necessary for selecting the desired marking position on the foil. The primary differences between the two systems were as follows: the laser marking system required a safety enclosure to prevent hazardous laser radiation exposure and an exhaust system to avoid contamination from particles. In contrast, the ink marking system was safer and simpler to integrate but required a consistent ink supply. In Figure 14, the integration of the two different marking systems is shown.

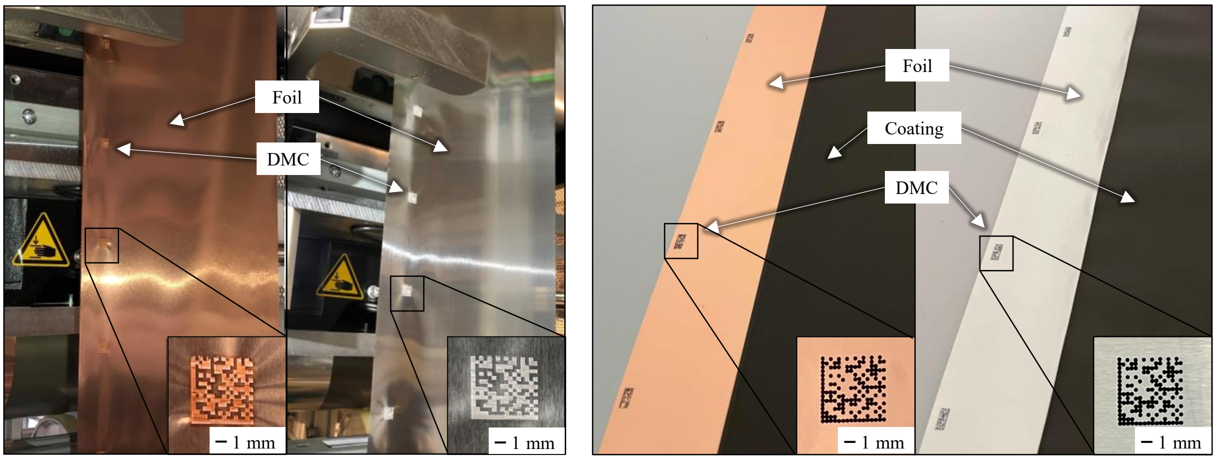

Figure 14: Left: Inline laser marked foils with applied DMCs. Right: Inline ink marked electrodes with applied DMCs; figure adapted from SOMMER ET AL. (2023a).

The integrated markings enabled the assignment of production data to individual electrode sections. By selecting a marking distance in feed direction that ensured each electrode sheet had a marking after the coil was separated, these segmented sections could be referred to as virtual electrodes. The production data assigned to these virtual sections corresponded to the product and process data of the later individual electrode sheets. The inline marking systems presented allowed the placement of markings on the electrode current collectors, enabling the segmentation of the continuous electrode by using reading devices at stationary points decoded these markings for data allocation.

For validation of the implemented marking systems, the inline measured electrode areal mass loading of the dry coating, measured by a non-contact traversing system, was compared to the offline measurement of electrode weight using a high-precision balance. The applied markings were read in parallel with the areal mass loading measurements using a reading device. Offline measurement involved decoding DMCs at intervals of 1.5 m along the produced cathode, cutting samples, and determining weight using a high-precision balance to calculate areal mass loading. The recorded inline data were compared to the offline measurements. The results showed that the inline measured loadings had a high alignment with the offline measurements, with an average deviation of 1.6 %. Deviations were explained by uneven coating distribution at the electrode edges.

Key Findings

The KFs of the publication SOMMER ET AL. (2023a) are summarized as follows:

KF 1: Both marking systems require straight, vibration-free foil movement and a consistent marking distance. Laser marking demands a safety enclosure and an exhaust system to handle hazardous radiation and material particles, whereas the ink marking system is simpler and safer to integrate but requires a steady ink supply.

KF 2: The integration of laser and ink marking systems allows for the inline segmentation of continuous electrodes, enabling the assignment of production data to individual electrode sections.

KF 3: The results demonstrated that electrode areal mass loading could be assigned using an inline marking system with DMCs on segmented electrodes. This validation showed that it was possible to trace all recorded product and process parameters from continuous process steps to individual sections through inline segmentation.

Contribution of the Authors

Alessandro Sommer designed and integrated the inline laser marking system for the *iwb* production line, conducted the experiment, and analyzed the results. Steffen Bazlen integrated the inline ink marking system on the production line of the Center for Solar and Hydrogen Research Baden-Württemberg (ZSW) with the support of Hai-Yen Tran. Together, the algorithms for segmenting production data in electrode manufacturing were developed. Wolfgang Braunwarth and Rüdiger Daub edited the publication.

4.6 Publication IV: Integration of an Electrode-Sheet-Based Traceability System into the Manufacturing Process of Lithium-Ion Battery Cells

Summary

The publication detailed a method for tracking and tracing individual electrode sections throughout the battery manufacturing process, from coating to formation. By focusing on the areal mass loading, the traceability system demonstrated that production data could be automatically linked to each electrode sheet. Similarly, data from cell assembly and finalization could be associated with each cell stack and its constituent electrodes. This approach allowed for monitoring the areal mass loading of each electrode sheet, identifying deviations, and calculating cell-specific capacities from the manufactured battery cells.

In Figure 15, the general procedure for implementing the traceability system in battery production is depicted. This procedure consists of four key components: marking, identification, data acquisition, and data allocation, and is applied specifically to electrode production and cell assembly.

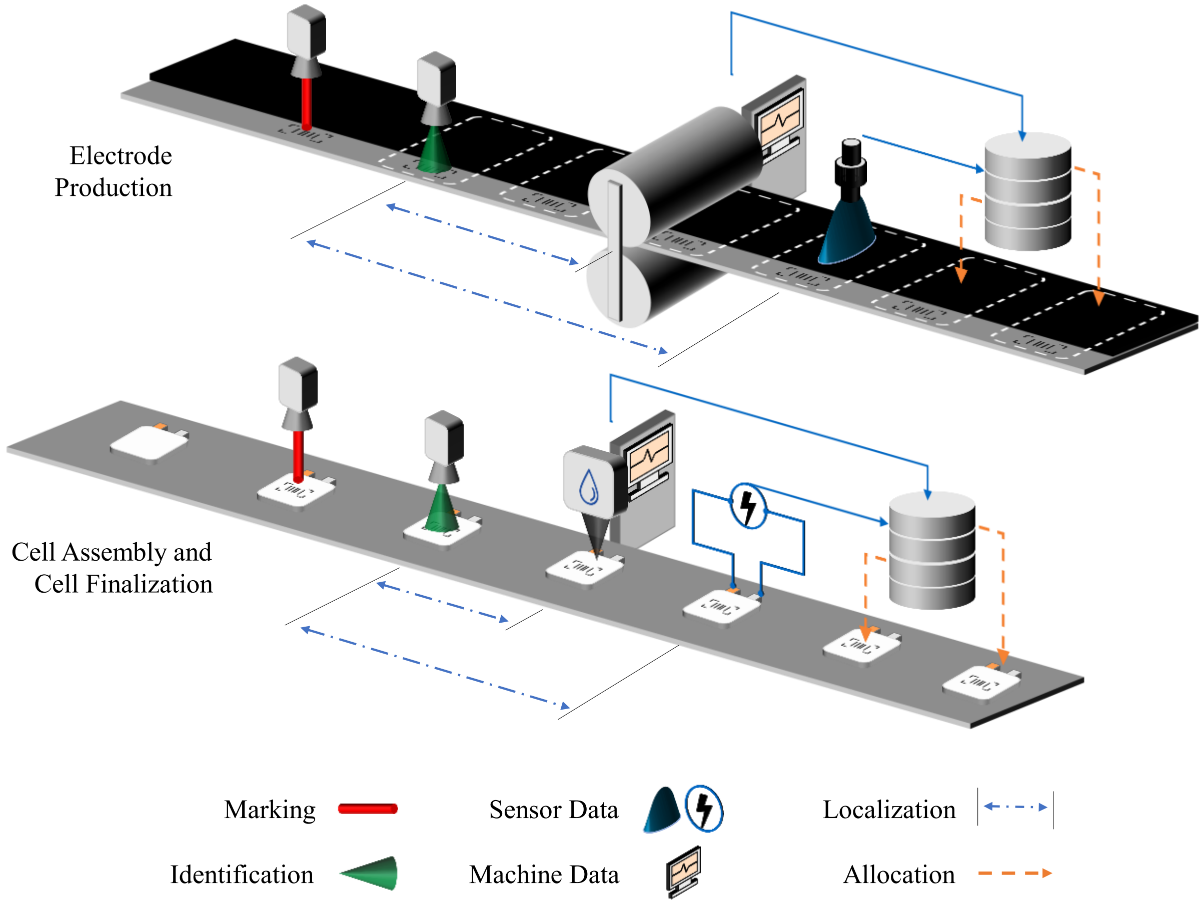

Figure 15: Marking, identification, localization, and allocation of production data are required for complete traceability down to the electrode level over the entire cell production process chain in electrode production, cell assembly, and cell finalization.

To validate the traceability system, theoretical capacities calculated from the traced inline data were compared with the actual measured capacities of the cells after formation. The method involved analyzing the mean areal mass loading and standard deviations of the electrode sheets in various cells. The electrodes, coated on both sides with specific targets, showed that measured values were within acceptable tolerance limits, with deviations primarily attributed to the coating process. Capacities were calculated by summing the averaged areal mass loadings of individual electrode sheets, and comparisons between measured and calculated capacities generally showed good agreement. Deviations were explained by variations in the coating process and manual handling during assembly. Applying this approach to different production runs provided insights into the relationship between the cathode areal mass loading and the cell capacity.

The system demonstrated that the electrode-sheet-based capacity calculations were highly accurate, showing a deviation of no more than ≤ 1.1 %. compared to the actual measured values. This confirmed that the traceability of areal mass loading down to the electrode-sheet level was ensured across the entire production chain. The adaptability of the method to various production parameters suggested that it could precisely assign and trace other production data as well. Validation across different production lines showed that a traceability system could be integrated into lines at various stages of technological readiness. However, the accuracy of traceability depended on the quality of sensor technology and data recording speeds. Higher production speeds could limit the ability to provide detailed areal mass loading data for all electrode sheets, affecting system accuracy.

Key Findings

The main KF of the publication SOMMER ET AL. (2024b) are as follows:

KF 1: The application of the traceability system effectively tracks and traces individual electrode sections from coating to cell formation, linking production data to each electrode sheet and cell stack for precise capacity calculations.

KF 2: The capacity calculations based on the tracked production data closely matched actual measured capacities, with only minor deviations, confirming the reliability of the system in assessing battery cell performance.

KF 3: The functionality of the traceability system is demonstrated using the product parameter areal mass loading. This validation ensures the traceability of all other production parameters, including those that cannot be measured retrospectively.

KF 4: The precision of the traceability system is dependent on sensor technology and data recording speed. Higher production speeds can reduce data accuracy, emphasizing the need for advanced sensors and recording methods to ensure precise traceability.

Contribution of the Authors

Alessandro Sommer and Steffen Bazlen planned, conducted, and analyzed the approach and the experiments. Hai-Yen Tran and Jannis Wachter assisted with the execution of the experiments, while Wolfgang Braunwarth and Rüdiger Daub edited the publication.

4.7 Publication V: Determination of Electrode Balancing in Multilayer Pouch Cells Through Tracking and Tracing in Lithium-Ion Battey Production

Summary

The publication aimed to demonstrate the effectiveness of a traceability system in battery cell production for determining the electrode balancing in multilayer pouch cells. Therefore battery cells were produced, and production deviations were intentionally introduced by incorporating electrode sheets with excessive areal mass loading into the stacking process of the pouch cells. Both reference cells and manipulated cells were used, with the manipulated cells featuring an electrode sheet with excessive areal mass loading. The traceability system recorded all the electrode sheets and created a digital twin of a manufactured battery cell. This allowed for precise calculation of the N/P ratio for opposing electrode sheets. A schematic of a virtual cell stack is shown in Figure 16, illustrating the areal mass loading values of all electrode sheets on both sides of a manufactured battery cell, as well as the resulting N/P ratios between the cathode and anode.

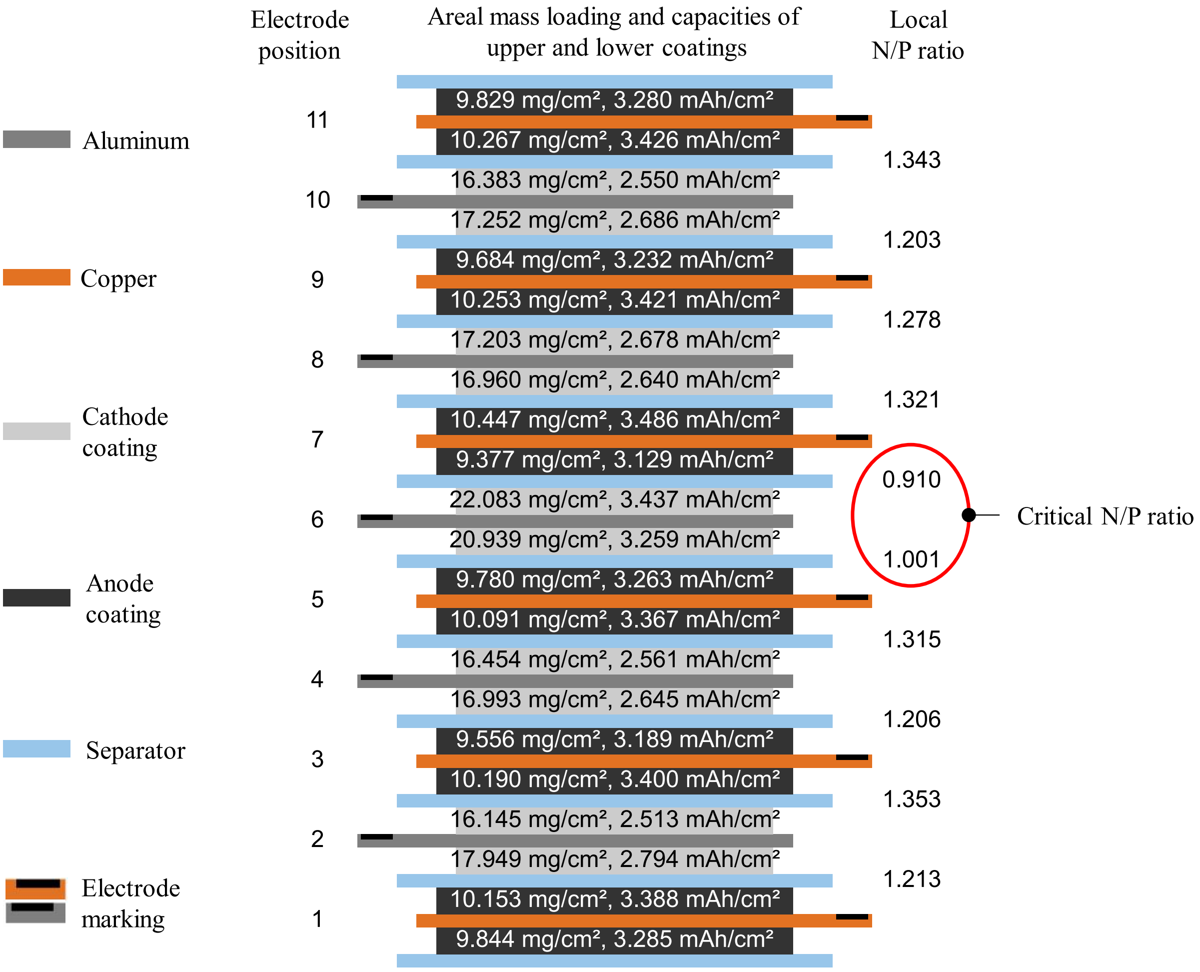

Figure 16: Schematic representation of the electrode sheet-specific areal mass loadings, calculated areal capacities, and the resulting N/P ratios for the individual layers of an exemplary manufactured battery cell, including production deviations. The critical N/P ratio, caused by the manually introduced overloading of the cathode sheet, is marked in red; figure adapted from SOMMER ET AL. (2024a).

Subsequently, all produced cells, including the reference and manipulated cells, were subjected to a cycle life test.

The study found that deviations in the electrode areal mass loading, in this case demonstrated with manually introduced cathodes that exceeded tolerance limits, led to imbalanced N/P ratios and accelerated aging of the cells. The excess areal mass loading of the cathode caused local lithium plating on anodes, resulting in increased capacity loss during cycling.

The traceability system was crucial in detecting production deviations and offering insights into how electrode balancing impacts cell performance. It revealed that even small deviations from the specified tolerances could result in significant quality issues and accelerate the degradation of the battery cells. Post-mortem analysis of the battery cell confirmed these findings and demonstrated that electrode IDs remained readable for traceability purposes.

The results of the study suggested that the traceability system could be used for innovative analyses, such as sensitivity analyses of coating data, to establish quality gates and improve production processes. Overall, the traceability system facilitated a better understanding of how production variations affected battery performance and allowed for more effective pre-sorting of electrodes to enhance cell quality.

Key Findings

The KFs from the publication of SOMMER ET AL. (2024a) can be listed as follows.

KF 1: By using traced data, digital representations of cell stacks were created. The digital model enabled detailed analysis of the local N/P ratios and electrode balancing within each cell stack, highlighting how production variations affect battery performance.

KF 2: The traceability system allowed for the precise detection of production errors by tracking and analyzing detailed electrode data, enabling accurate identification of deviations and their impact on cell performance.

KF 3: The traceability system effectively linked production data with cell performance, showing that variations in the electrode areal mass loading and the N/P ratios directly impacted battery cycling stability and capacity.

KF 4: The data collected through the traceability system offered the potential for advanced analyses, including sensitivity analyses of coating data and the determination of quality gates for manufacturing processes. This capability supports continuous improvement in production quality and battery performance.

Contribution of the Authors

Alessandro Sommer designed, conducted, and analyzed the experiments. Jannis Wachter assisted with the experiments and analysis. Sophie Grabmann and Rüdiger Daub edited the publication.

4.8 Publication VI: Analysis of Quality-Relevant Process-Structure Relationships Through Tracking and Tracing: A Comprehensive Study on the Calendering Process in Lithium-Ion Battery Production

Summary

In this publication, the application of the traceability system has shown how the fine-grained database can be used to create a deep understanding of the process. This work aimed to describe the compaction behavior of an electrode and its effects on product properties using a marker-based traceability system. A commercially procured electrode was marked with a laser system in the coating machine of the *iwb* and used as the test specimen. The electrode was then calendered in steps of increasing pressure, with inline measurement data assigned to specific electrode sections (ES). After calendering, offline measurements of the electrode thickness, the particle indentations, the porosity, the interface resistance, and the adhesion strength were measured and linked to the corresponding electrode sections. The linkage between offline data and inline production parameters was established through markings on the current collector of the electrodes, allowing for correlations between production data to be derived. In Figure 17, the linking data regarding inline and offline measurements are shown.

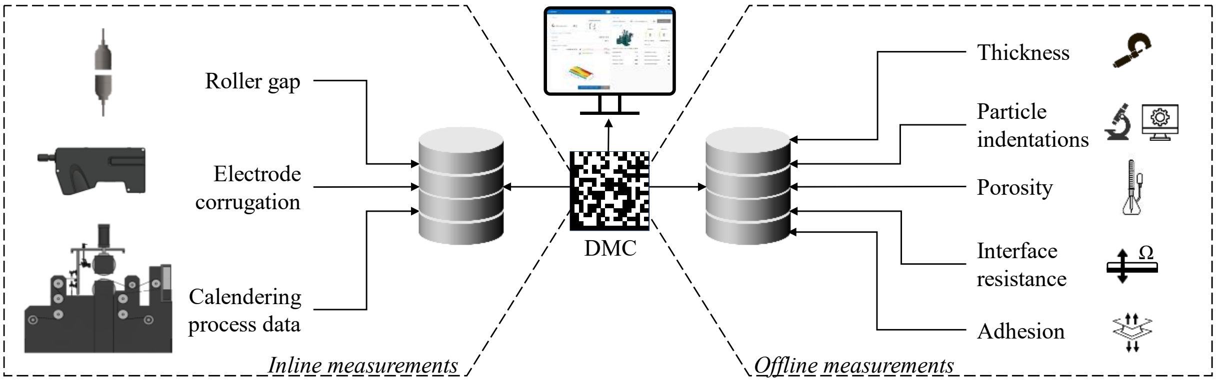

Figure 17: Periphery of the calender for the investigations, divided into inline and offline measurements. The marking on the individual electrode sections forms the interface between the two measurement data areas and allows the data to be linked consistently. Figure adapted from MAYR ET AL. (2025).

In this experiment, the cathode labeled with DMCs was calendered in stages with a rolling force initially set at 350 kN. Every approximately 7 meters, the target pressure was gradually reduced by 50 kN, defining distinct ES based on the set pressure stages. The calender maintained stable pressure throughout, enabling clear identification of each ES. Each DMC served as a data point within the respective ES. For a reference area of the electrode, the calender was opened, indicated by 0 kN pressure, but measurements continued for the non-calendered electrode both inline and offline.

During calendering, the gap between the rollers was measured, revealing a linear relationship between the calender pressure and the gap size. As pressure increased, the gap decreased, resulting in more densely compacted electrodes. This linear behavior allowed accurate prediction of the calender gap based on pressure. The electrode thickness was investigated, showing a decrease with increasing pressure, reaching a minimum of approximately 125 µm at 350 kN. However, the decrease in the thickness showed a weakening trend at higher pressures. The porosity was calculated using both the gauge-measured electrode thickness and a pycnometer. Initially, the uncalendered electrode had a porosity of about 46 %, decreasing to approximately 25 % at 350 kN. The trend of decreasing porosity with increasing pressure was evident, though less pronounced at higher pressures. The defect evaluation index (DEI) was used to measure the electrode wave amplitude. The highest pressure resulted in the most pronounced corrugation, while the uncalendered sample had the lowest DEI and showed no visible waves. This quantitative measurement of the electrode waves allowed defects to be traced back to specific process parameters, highlighting the importance of avoiding excessive corrugations for better electrode processability. The electrical interfacial resistance was examined, showing the highest resistance in the uncalendered state. The electrical resistance decreased with increased calendering pressure, following a hyperbolic trend. The investigation of the adhesion strength showed that it decreases as calendering pressure increases, reaching a local minimum. The adhesion strength rose sharply with further increases in calendering pressure. Through the stepwise increase in calendering pressure for the respective ES, the relationships between the adjusted process parameters and the resulting product parameters could be demonstrated in fine detail. This approach provided a comprehensive understanding of how small variations in process parameters affect the final electrode properties.

With the use of the traceability system, it was possible to gradually demonstrate both qualitatively and quantitatively the relationship between the set machine parameters and the resulting product properties. From this, the necessary process parameters for the targeted adjustment of product parameters can be derived.

Key Findings

The following KFs of the publication MAYR ET AL. (2025) can be recorded as follows.

KF 1: Inline and offline measurement data can be efficiently linked with the help of the applied markings on the electrodes to expand the data basis for intermediate product characterization.

KF 2: The combination of inline and offline data revealed the relationship between machine parameters and product properties, enabling the derivation of process parameters for targeted adjustments.

KF 3: By using a step-by-step test plan, the product-process behavior can be displayed in high resolution. Process parameters for specific product parameters can be efficiently derived from this.

Contribution of the Authors

Andreas Mayr and Alessandro Sommer designed, carried out, and evaluated the investigations together. Both contributed equally to the creation of the publication. Julian Link and Johannes Schachtl provided support in carrying out the experiments. Rüdiger Daub edited the publication.

5 Discussion of the Findings

This chapter discusses the results from publications (P I–VI), focusing on a comparison with existing scientific knowledge and the current state of the art, along with a critical reflection on the findings. The publications demonstrate how a marker-based traceability system can be implemented for processes resolved at the electrode sheet level, illustrating its potential for fault detection and for enhancing process understanding. The key results achieved are summarized as follows:

Publication I presented a concept for a traceability system in battery cell production. The focus was on the process-related and technological requirements and solutions. Compared to the state of the art, the data granularity and the limits of the system to be designed were defined for the first time. In the system presented, all intermediate products down to individual electrode sheets were to be characterized in a traceable or data-based manner. Furthermore, it was determined that the identification of the individual electrode sheets should take place via a physically applied marking and that ink and laser markings proved to be promising. Requirements for the durability of the applied markings were then derived from the boundary conditions of battery cell production.

Publication II presented the evaluation and assurance of the durability of physical markings for a comprehensive traceability system in battery cell production. Unlike the state of the art, experimental studies on the suitability and durability of ink and laser markings were conducted for the first time. The influence of the markings on the process chain, and vice versa, was also analyzed. It was found that the markings needed to meet specific geometric specifications regarding format, content, size, and available space on the current collector foils. Additionally, they had to withstand high temperatures during coating, drying, and calendering, as well as chemical influences from solvents. The potential weakening of the foils caused by the laser markings was also examined to ensure that it did not impair the processability of the current collector foils. The tests revealed that the specific requirements had to be individually checked depending on the production line. Using the *iwb* production line as an example, it was demonstrated that both marking technologies were suitable.

Publication III involved the development and validation of methods for inline segmentation of electrodes during the coating process. While marking systems were already known in existing technology, this publication introduced a novel combination and integration of ink and laser marking technologies specifically for electrode coating. Specific technical requirements and adaptations for the integration of the marking systems were presented. In addition, the publication showed how the inline segmentation of electrodes by means of markings enabled fine-grained traceability that went beyond the state of the art.

Publication IV focused on the development and validation of methods for the traceability of individual electrodes throughout the entire battery cell production, from mixing to the formation process. The new method demonstrated how production data was automatically linked to individual electrode sheets and how data from cell assembly and finalization was assigned to the respective cell stacks and their components. Additionally, the overall system was validated using a suitable product parameter, which had not been described in the state of the art. The validation involved comparing theoretical capacities calculated from inline data with the actual measured capacities of the cells after formation. The method proved effective and could be integrated into various production lines.

Publication V was the first to demonstrate the use of a traceability system in battery cell production. To date, neither a functioning, validated traceability system nor its application had been described in the state of the art. The work highlighted the effectiveness of the system by using it to determine the electrode balancing in multilayer pouch cells. The system enabled tracking of the areal mass loading and the stacking sequence of the electrodes, allowing for the creation of virtual representations of the produced cell stacks. This made it possible to precisely calculate the N/P ratio between opposing electrode sheets, a method not previously described in the state of the art. The traceability system demonstrated that even minor deviations could lead to significant quality issues and accelerate the degradation of the battery cells.

Publication VI showed how a more in-depth understanding of the process could be achieved using a fine-grained data basis created by a marker-based traceability system. In the state of the art, no application of a traceability system was previously described that supported the development of process understanding. The traceability system made it possible to assign inline data to specific electrode sections and link these to offline measurements such as thickness, porosity, particle imprints, and adhesion strength. The publication demonstrated how different calender pressures, divided into specific ES, provided a precise understanding of the effects on density, porosity, and surface waves of the electrodes. The system enabled a clear correlation between pressure levels and the resulting physical properties of the electrode.

This research introduced a novel marker-based traceability system for electrode sheet-resolved processes in battery cell production, significantly exceeding the state of the art in deviation and error detection as well as process understanding. Unlike previous systems, this new approach tracked individual electrode sheets throughout the entire manufacturing process, from mixing to formation, allowing for more granular data on product parameters that had not been previously accessible. For the first time, physical markings were used to identify electrode sheets, with a focus on ensuring their durability under the demanding conditions of battery cell production. The innovative integration of ink and laser markings enabled inline segmentation during the electrode production, providing fine-grained traceability that went beyond what was described in existing technology. This new method captured production fluctuations more accurately and ensured a deeper understanding of the effects of process variations. The system automatically linked production data to electrode sheets, tracking them through cell assembly and finalization. This capability was validated offering a level of traceability that had not been achieved before. Furthermore, the system facilitated a more detailed understanding of process parameters by linking inline data to offline measurements. By correlating these product parameters with certain process settings, it was possible to gain insights into process optimization that were previously only possible with increased experimental effort.

In the work described, production data was assigned in a 1D format to the intermediate products, meaning that each electrode sheet was associated with a scalar, discrete data set to represent its status. For example, each electrode sheet was assigned a specific value for the measured areal mass loading. While this 1D approach provides useful information, a 2D resolution and assignment of data could offer a more comprehensive understanding of the actual condition of the intermediate products. By incorporating 2D data, fluctuations or deviations that might be overlooked when averaging measurement data could be detected. This would enable more detailed and extended analyses of the production process and product quality. Initial studies on 2D data tracking have already been explored in the work of LINDENBLATT ET AL. (2024), suggesting that such an approach holds promise for enhancing traceability systems and offering a deeper insight into variations that could affect the final product's performance. The shift to 2D data could thus represent a significant step forward in refining process monitoring and improving quality control in battery cell production.

Another potential improvement is increasing the data resolution on electrode sheets. In the described studies, each electrode sheet was assigned a single marking and data set. However, adding more markings per sheet would enhance the resolution of the data. This approach is particularly beneficial for long electrodes, such as those used in cylindrical cells, as it reduces inaccuracies and provides a more precise representation of production fluctuations. The proposed adaptation involves assigning multiple markings to different segments of each electrode sheet, allowing for a more detailed tracking of variations across the entire electrode. This enhanced resolution could lead to better monitoring of the production process, improving both process control and product quality.

Furthermore, the focus was placed on physical markings for the identification of electrodes throughout the manufacturing process. Regardless of whether an ink or laser system is used, the respective consequences of each system must be carefully considered, which requires experimental validation. An innovative approach explored is the identification of individual electrode sections using so-called *fingerprints*. This method involves recognizing unique structures on the electrode surfaces. Such a technique could potentially replace physical markings, thus reducing integration costs. Initial investigations have already shown that structures or *fingerprints* in the coating or on the current collector foils (RIEXINGER ET AL. 2023) or through coating defects (SCHOO ET AL. 2023) can be recognized.

While this dissertation focuses on the design, implementation, and validation of a holistic traceability system, a detailed assessment of the trade-off between implementation effort and expected benefits was not within its scope. Evaluating the practical costs, organizational requirements, and potential gains of fine-grained traceability represents an important direction for future research. Such an analysis would help identify scenarios in which the benefits of improved process transparency, defect analysis, and data-driven optimization justify the associated effort, providing guidance for industrial adoption and decision-making.

6 Conclusion

6.1 Summary

Expensive materials and high reject rates result in cost-intensive scrap, which must be reduced to achieve an economical and ecological battery cell production. Quality gates and data-driven approaches make it possible to identify defective intermediate products and enhance the general understanding of the process. However, this requires a consistent and comprehensive data basis.

The aim of this work was to demonstrate the added value of using a traceability system in battery cell production, which required an adapted traceability concept. A core element of the system was the identification of the smallest TRU, in this case, a single electrode sheet. This provided the foundation for a fine-grained data set, enabling the batch-by-batch observation and segmentation of the continuous process steps. A suitable marking strategy had to be developed to ensure the unmistakable identification of intermediate products throughout the entire process chain. The individual components of the traceability system were then connected and validated across the entire process. Once the functionality of the traceability approach was successfully demonstrated, the system was implemented. It was shown that the traceability system could detect defective intermediate products at an early stage. Additionally, the traceability system was applied to systematically expand process understanding, with the calendering process serving as an example.

6.2 Outlook

Based on the traceability system developed, innovative applications and further improvements can be derived. The newly created data basis can be used to set up quality gates. This means that the generated and assigned production data of the intermediate products can be accessed and checked before each process step to ensure that certain target parameters are within the permissible tolerances. For example, a complete control of the product parameters from the electrode production can be carried out after the electrode sheets have been separated, followed by the sorting out of defective intermediate products.

The data-driven approaches described in the state of the art can be applied to the associated production data and exploit their full potential. With the support of this work, the data basis for this can be created through the traceability system and avoids complex experimental investigations. A traceability system provides the production data continuously in parallel with production so that ML algorithms can be continuously adapted and refined. This makes it possible to effectively identify unknown cause-and-effect relationships.

Another innovative approach is to provide the assigned production data of the intermediate products to the subsequent process step for quality prediction. This allows to react to production fluctuations or errors in advance. For example, a calendering system can use the coating data to determine when certain areas on the electrode need to be calendered or where adjustments are required due to a fluctuating loading. This can help to save energy and provide additional tool protection.

When using new battery materials on existing production lines, it is often necessary to adjust process parameters to achieve the desired product properties. An integrated traceability system helps efficiently determine product-process interactions through appropriate test plans. Production data can be continuously recorded with minimal material costs. These ongoing evaluations enable the quick identification of optimal process parameters based on the resulting product properties.

By comprehensively characterizing intermediate products using production data, deviations can be addressed in a targeted manner. Intermediate products that do not meet the desired target values but still maintain high quality can be further processed and sold as B or C class products. For example, in battery production, electrodes that are coated too thinly or too thickly can be specifically combined, rather than being discarded as rejects.

For upcoming regulations and legal requirements, such as a European battery pass, the traceability system can be used to provide the necessary data quickly. Desired parameters, such as the material composition of the electrodes, can be efficiently extracted from the system and made available. The system also enables rapid adaptation for changes in legal requirements so that the required data is always up-to-date and complete.

The added value of a traceability system in battery cell production can be additional increased, if it is possible to link the data from the operation of the battery cells with the production data. By integrating the operating and performance data of the batteries during their use with the detailed production and test records, more precise conclusions can be drawn about the quality and performance of individual battery cells. This enables a more comprehensive analysis of correlations between manufacturing conditions and subsequent performance parameters, identifies potential weak points in the production process and supports targeted optimization. In addition, such systems can help to diagnose problems more quickly and initiate targeted improvement measures.

Future work should investigate the scalability of the proposed traceability system with regard to increasing data volumes in industrial-scale battery manufacturing, as well as practical challenges related to industrial deployment, such as decentralized data generation, data ownership, and alternative data storage and database architectures. In addition, further research is required on effective methods for querying and analyzing traceability data, including the identification of relevant search patterns and the detection of similarities across recorded production situations.

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Appendix

A1 Overview of Supervised Student Research Projects

Within the scope of this dissertation, student research projects were supervised by the author of this thesis in terms of content and organization. The supervision was performed at the *iwb* of the TUM. Some of the jointly gained insights have been incorporated into this dissertation and the publications described in Chapter 4. The author would like to express his sincere gratitude for the inspiring discussions and the enormous support during the elaboration of the results.

Name	Student Research Project
Schwarz, N.	Bachelor's Thesis: Identification of Suitable Marking Methods for Electrode Sheets in the Production of Lithium-Ion Batteries (2020)
Hoops, J. F.	Interdisciplinary Project: Development of a Digital Material Platform for Innovative Cell Materials (2020)
Thole, A.	Interdisciplinary Project: Development of a Digital Material Platform for Innovative Cell Materials (2020)
Weishäupl, L.	Semester Project: Development of a Tracking and Tracing Concept for the Lithium-Ion Battery Production (2021)
Juhás, J.	Master's Thesis: From Prototype to Production System: Development and Implementation of a Web Application for Dynamic Analysis of Battery Performance Data (2021)
Rank, C.	Semester Project: Evaluation and Validation of Performance Analysis for Lithium-Ion Battery Cells (2021)
Santoso, M. R.	Semester Project: Experimental Influence Analysis for the Production of Small-Format Battery Cells (2021)
Lampelsdorfer, V.	Bachelor's Thesis: Development and Implementation of Concepts for UX Improvements of a Digital Research Platform for Battery Technologies (2022)
Gräf, L.	Semester Project: Tracking & Tracing in Battery Cell Production (2022)

Keßler, T.	Semester Project: Development and Cross-Server Automation of Data Structures for Efficient Processing of Battery Measurement Data (2022)
Knefel, P.	Master's Thesis: Integration and Commissioning of a Marking Unit in a Research Production Line for Lithium-Ion Battery Cells to Enable Tracking and Tracing Applications (2022)
Schwarz, N.	Semester Project: Development of a Discrete-Event-Simulation for a Tracking and Tracing System in the Battery Cell Production (2022)
Weishäupl, L.	Master's Thesis: Commissioning and Application of a Tracking and Tracing System for the Lithium-Ion Battery Production (2022)
Hirschberger, M.	Interdisciplinary Project: Database and Web Programming for Battery Production (2022)
Geitner; M.	Interdisciplinary Project: Database and Web Programming for Battery Production (2022)
Wachter, J. G.	Master's Thesis: Implementation and Application of an Electrode-Sheet-Based Tracking and Tracing System for the Lithium-Ion Battery Production (2023)
Weißenburger, F.	Bachelor's Thesis: Application of a Tracking and Tracing System in the Calendering Process of Lithium-Ion Batteries (2024)
Burger, T.	Master's Thesis: Integrated Traceability Solution and Data Analysis for Solid-State Battery Production: Concept, Implementation, and Cloud Integration (2024)

A2 List of Embedded Publications

Publications Incorporated Into This Dissertation

The following list includes the publications of the author in the context of this dissertation, in which he was either the lead author or shared first authorship.

Publication I: SOMMER ET AL. 2021
Sommer, A.; Leeb, M.; Haghi, S.; Günter, F. J.; Reinhart, G.: Marking of Electrode Sheets in the Production of Lithium-Ion Cells as an Enabler for Tracking and Tracing. Procedia CIRP 104 (2021) 2, p. 1011–1016.
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Further Publications of the Author:

The following publications were additionally written during the time as a research associate at the *iwb*:

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