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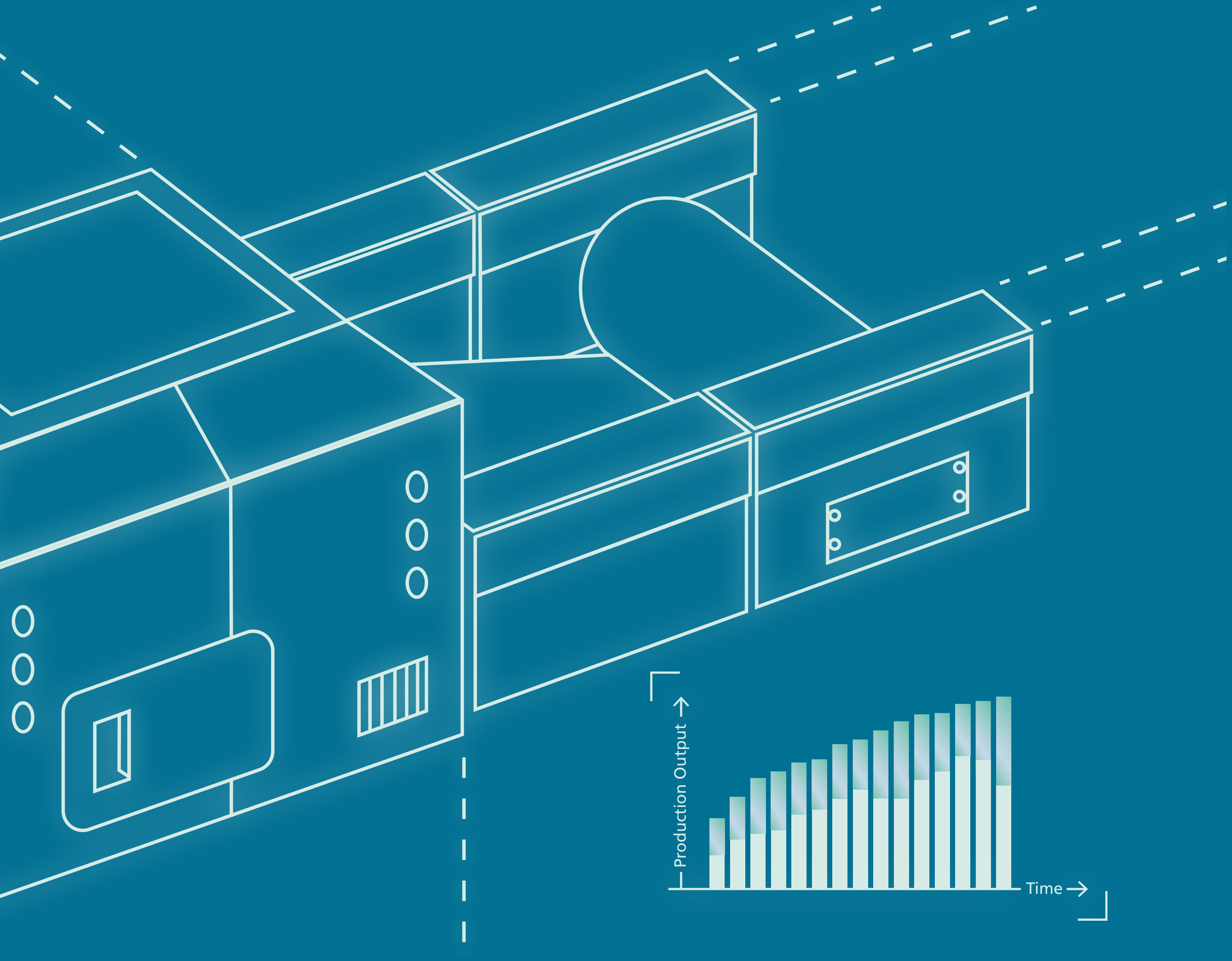


Mastering Ramp-up of Battery Production

Executive Summary

The shift to electric vehicles has led to a substantial increase in demand for battery cells. However, many newly established and even experienced manufacturers are struggling to meet production targets, facing overly high scrap rates and delayed start of production. These circumstances significantly impact profitability and the overall project viability. This white paper outlines the organizational and technical hurdles involved in ramping up a gigafactory. It also examines the potential consequences of these challenges, offering insights into how to overcome them and effectively manage this process.

The ramp-up process in battery cell production is highly complex and significantly deviates from idealized models due to various technical and organizational factors. Key challenges include the complexity of both the product and process, the novelty of battery production in regions like Europe and the U.S., the scale and automation level of facilities, the availability of skilled workers. Additionally, cultural, and linguistic barriers can further complicate operations. These issues often lead to setbacks and deviations from initial plans, highlighting the importance of having strategies to manage these complexities effectively. Structured training programs, digital knowledge repositories, and continuous learning platforms are essential to ensure that critical information is communicated across all levels of the organization.

When ramping up battery production, numerous technical challenges emerge, with electrode coating and drying being key areas due to their critical importance for final cell quality. The difficulty lies in scaling production, optimizing process parameters, and managing defects. Addressing the intricate interdependencies between process and quality parameters requires the use of systematic root cause analysis (RCA) to identify and resolve production issues.

Digitalization plays a pivotal role in optimizing production, with efforts to reduce implementation costs and maximize benefits through modular IT architectures, standardized data models, and advanced data analysis techniques. By integrating expert knowledge (e.g., error catalogs) with data-driven methods (e.g., traceability), manufacturers can enhance troubleshooting and drive continuous improvement. This approach enables high-quality production to be achieved early in the ramp-up phase. To fully harness the power of digitalization, a modular and flexible IT architecture should be implemented, supported by multiple optimized databases and high-performing hardware. Standardized data models, such as OPC UA Companion Specifications, further streamline machine integration and data access.

The white paper was authored by researchers from the PEM chair at RWTH Aachen University and the Fraunhofer Research Institution for Battery Cell Production FFB, drawing on real-world case studies, data analysis, and best practices. Both Fraunhofer FFB and PEM provide the industry expertise, databases, digitalization solutions, and infrastructure necessary to support manufacturers in mastering the ramp-up process. The primary objective of this white paper is to demonstrate how these resources, along with strategic insights, can be leveraged to ensure a successful and efficient ramp-up.

Key Takeaways

1 The performance in the ramp-up phase is critical for the long-term success of the project. Internally caused underperformance – such as slow learning rates, low-capacity utilization, quality issues, etc. – combined with additional external events like weak EV demand, raw material price fluctuations, etc., can easily lead to doubts about the financial viability of the initiative.

2 Effectively managing organizational challenges – such as enhancing workforce skills, managing supply chain complexities, implementing effective change management, and ensuring compliance with standards and regulations – is crucial for success.

3 Data-supported root cause analyses provide a deep understanding of process interdependencies. Based on this insight, targeted quality measurements should be selected and implemented to effectively manage the overall process.

Content

1 Introduction

With the transformation from combustion engines vehicles to battery-powered electric vehicles, the demand for battery cells is increasing considerably. Worldwide, the forecasted demand for battery storage capacity in 2030 is between 2,500 and 3,500 gigawatt-hours annually. In Europe alone, the to date realized and announced battery production capacities amount to approximately 1,800 gigawatt-hours per year (see Figure 1). Key production sites include Germany, Hungary, and France. Among these producing companies are European start-ups such as Northvolt, PowerCo, ACC, etc. as well as established Asian battery cell manufacturers such as CATL, EVE, Samsung, LG, AESC, etc.

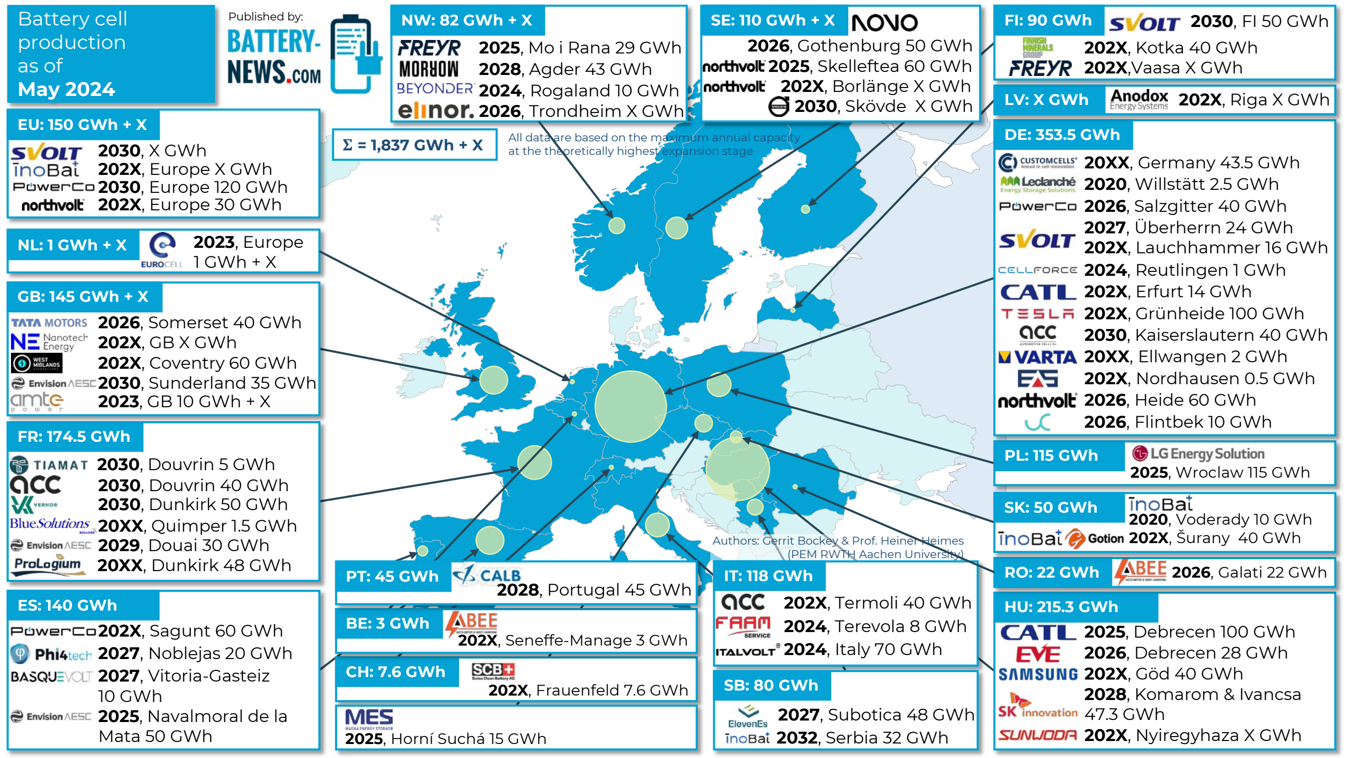
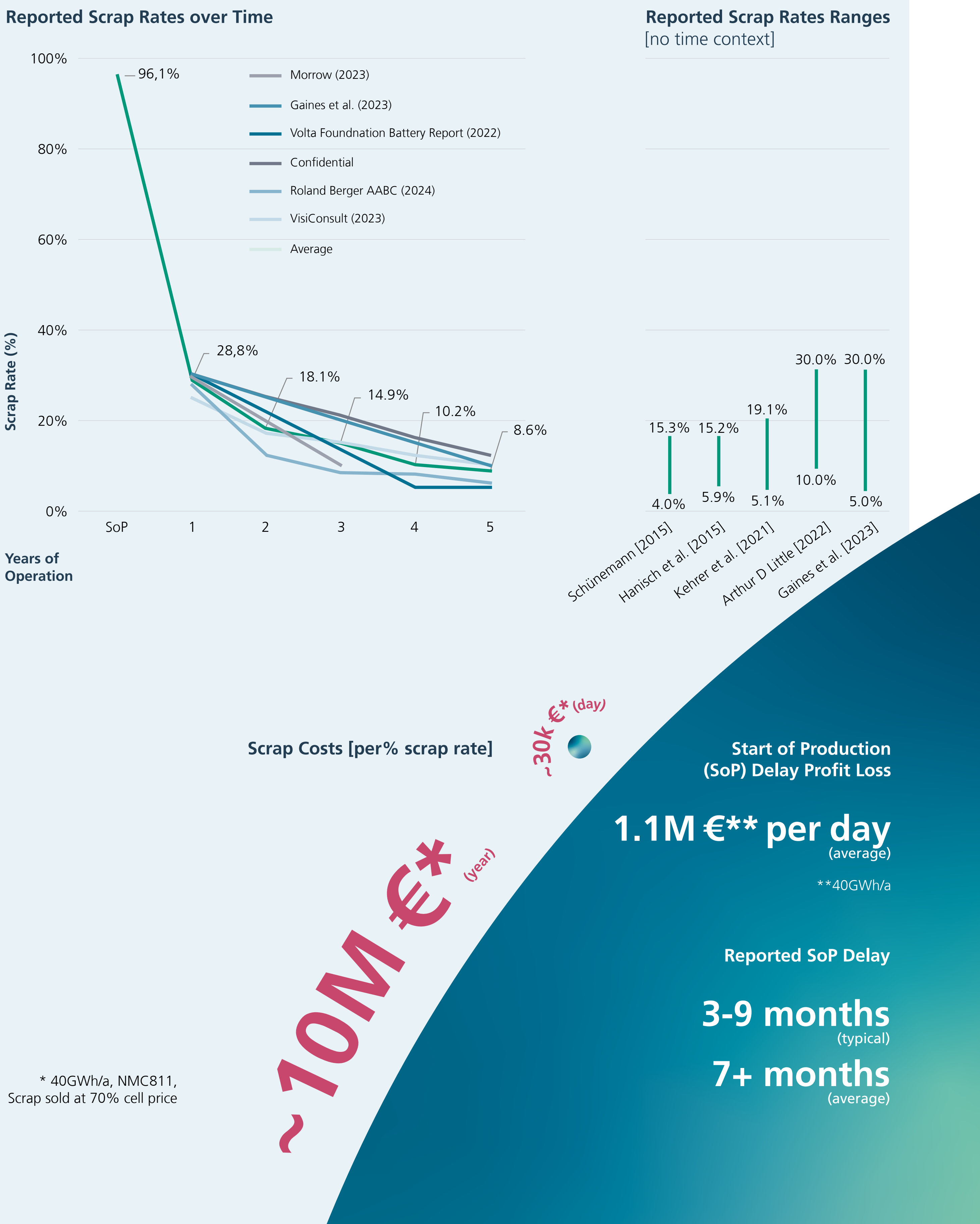


Figure 1 Overview of existing and announced gigafactory production of battery cells in Europe (source: battery-news.de).

The installation of battery factories is of high financial and strategic relevance for Europe as a business location. However, the last one-to-two years have shown that although many battery production facilities have already been built, the quantity of battery cells produced is far behind the announcements and expectations. The issue effects not only newly founded European companies but also to established Asian battery cell manufacturers.

Various analyses reveal a significant mismatch between the planned KPIs and the KPIs actually achieved by manufacturers. Relevant key performance indicators (KPIs) for a successful ramp-up include scrap rate, machine availability, production speed, and overall equipment effectiveness. Figure 2 illustrates lately reported general and ramp-up-related scrap rates in battery production, the resulting costs as well as the profit losses caused by delays for a 40-gigawatt-hour factory.

Figure 2 Overview of relevant ramp-Up procedure parameters and events.



Scrap rate ranges of 15 to 30 percent in the first years are common in battery production, and even after five years, scrap rates are still high with about ten percent. Each percent point of scrap rate costs about 30,000 euros a day and roughly ten million euros a year. Therefore, a scrap rate of 30 percent means costs of approximately 900,000 euros per day at full utilization. Additionally, each day of delay in the start of production (SoP) also cost a significant amount of money, namely 1.1 million euros of profit losses. Considering that the average delay of the SoP is often more than seven months and production then starts with a scrap rate of 30 percent or more, the business case of the entire factory is at danger. These figures apply not only to factories of European start-ups but also to established Asian cell manufacturers that intend to replicate their factory designs from Asia almost one-to-one in Europe.

2 Definition, Scope, and Targets of Ramp-ups

2.1 Production Ramp-ups

While ramp-up refers to the general process of gradually increasing capacity or performance in any context, production ramp-up specifically describes the transition from small-scale production – such as prototypes and first pre-series – to full-scale mass production, aiming for fully utilizing the nominal capacity. While initial prototypes and some pre-series units are typically produced in off-site technical centers or on pilot lines, the production process transitions to the designated series production system during production ramp-ups.

This transition requires careful planning, optimization, and coordination across various involved departments related to the production process. Ensuring efficient and consistent manufacturing in accordance with defined product specifications and quality standards is a challenge of both organizational and technical nature. Overall, the ramp-up phase can be divided into three distinct stages, often summarized and represented in a ramp-up curve (see Figure 3) which describes the temporal progression of production capacity utilization.

- **Pre-Series** Production: Initial stage that involves the manufacturing of small batches, characterized by controlled and iterative testing materials, products, and manufacturing processes.
- **Zero Series:** Units manufactured in series facilities under series conditions, while continuing to refine processes and ensure product consistency. The main goal is to ensure that manufacturing process and product itself are sufficiently mature to start production for customers.
- **Production Ramp-up:** Transition to full scale with gradual and consistent increase of production capacity, until planned production is attained.
- **Series Production:** Stable production of series products at the required output rate and in the quality specified by the customer.

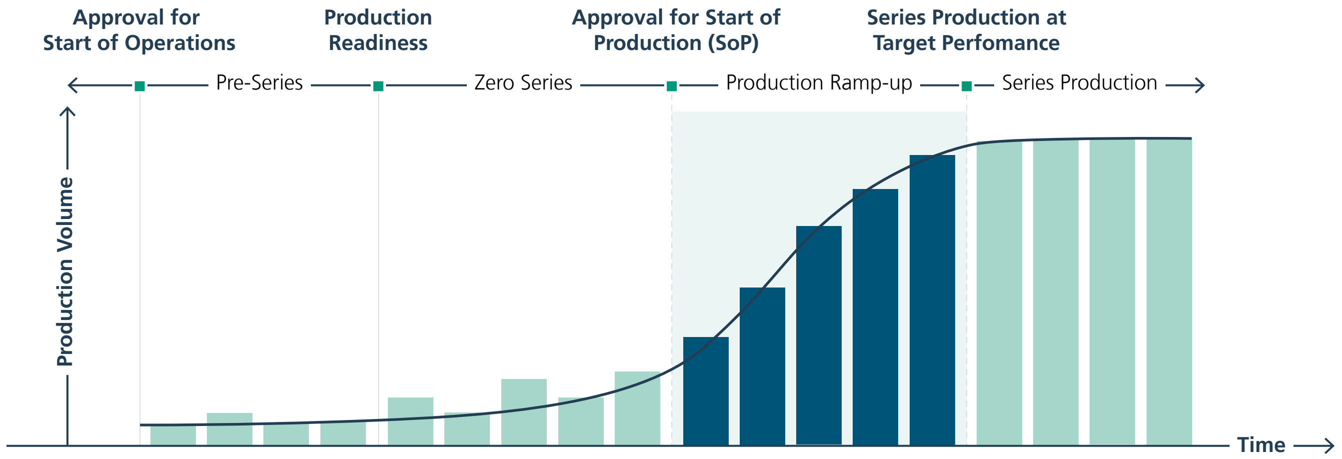


Figure 3 Idealized ramp-up curve with maturity milestones. (Note: In this context, production performance is recorded discontinuously, for example, by averaging the production performance during a shift).

The transition from zero-series to the production ramp-up phase often signifies the release for the start of production (SoP). With this milestone, operations focus on manufacturing the final product that meets customer specifications. During ramp-up, managing instabilities becomes a major challenge, where issues such as unexpected equipment failures, high process variability and final product changes must be effectively addressed. The end of production ramp-up marks a stage at which the production system is characterized by stabilized production, consistently meeting quality standards and approximating desired output rates. The multitude of production activities prior to achieving customer-ready production is handled by the ramp-up management. In literature, ramp-up management is described as "all activities for the planning, steering, implementation and controlling of the production Ramp-Up phase and under consideration of upstream and downstream processes" [1]. These activities contribute to achieving the core objectives of a successful ramp-up, which can be summarized as follows:

- **Risk Mitigation:** Identifying potential risks and developing initiative-taking strategies for mitigation.
- **Cost Minimization:** Managing and minimizing the costs associated with ramp-up activities, including production startup costs, logistics expenses, and potential overheads, to maintain financial efficiency.
- **Robust Production Systems:** Implementing and optimizing production systems to achieve stable and consistent manufacturing processes post-ramp-up, ensuring sustained product quality and operational efficiency.
- **Continuous Improvement:** Establishing a culture of continuous improvement throughout the ramp-up process to enhance productivity and product quality.
- **Accelerated Time-to-Volume and Time-to-Market:** Successfully reaching the" time-to-volume" milestone, which signifies the point at which production reaches planned output levels. Further streamlining the process to swiftly bring the product to market, allowing the organization to capitalize on market opportunities promptly and gain a competitive edge.

Overall, the production ramp-up is a challenging process, especially in battery cell production, as evidenced by recent delays in various cell production projects illustrate. Since the term "ramp-up" and the exact period it refers to are not uniformly defined, this chapter has provided the production-related definition used for this white paper, considering ramp-up management and its key objectives. The factors which influence the degree of difficulty of a production ramp-up are discussed in more detail subsequently.

2.2 Factors Influencing the Ramp-up Process in Battery Cell Production

Having defined the term "ramp-up" and outlined the individual phases of the process in the previous chapter, we now turn to the factors influencing this phase. As illustrated in Figure 4, the real-world ramp-up process often deviates significantly from the idealized curves presented in literature. Rather than a smooth, linear progression, it is typically marked by setbacks and deviations. Several factors, as highlighted in Figure 4, impact the efficiency and speed of this phase. These factors contribute to the challenges discussed in Chapters 3 and 4. The following section delves into these influencing factors and their specific impact on the characteristics of battery cell production.

The **complexity** in battery cell production can be seen in two ways: from the product perspective and from the production perspective. From the product perspective, battery cells are particularly complex because the functionality and behavior of individual components in later operation has not been fully investigated. Although electrode production has a major influence on cell quality, defects that occur here are sometimes only detected when the cells are formed (cause-and-effect relationships). A lack of knowledge makes it difficult to master these processes quickly during ramp-up. From the production perspective, a high level of complexity arises from the fact that many different processes are needed to manufacture a battery cell. Depending on how the production procedure is defined, up to 140 steps are required to manufacture an automotive traction battery cell. This does not even include testing processes and logistics. Additional complexity arises from the fact that not only discrete but also continuous processes are included in the process chain, which run at high speeds. This complexity leads to challenges in ramp-up, as multidisciplinary teams are required to master the heterogeneous process landscape. Furthermore, it becomes more difficult to coordinate processes if they are different in their type (discrete, continuous, batch).

Especially in Europe and the USA, there is a high **degree of novelty** about the battery cell product and the corresponding production. Although there is a growing research landscape and industry interest, there is a lack of experience in production due to a lack of production infrastructure. The greater a product's degree of novelty, the more challenging the associated production ramp-up is, which leads to longer start-ups and higher costs.

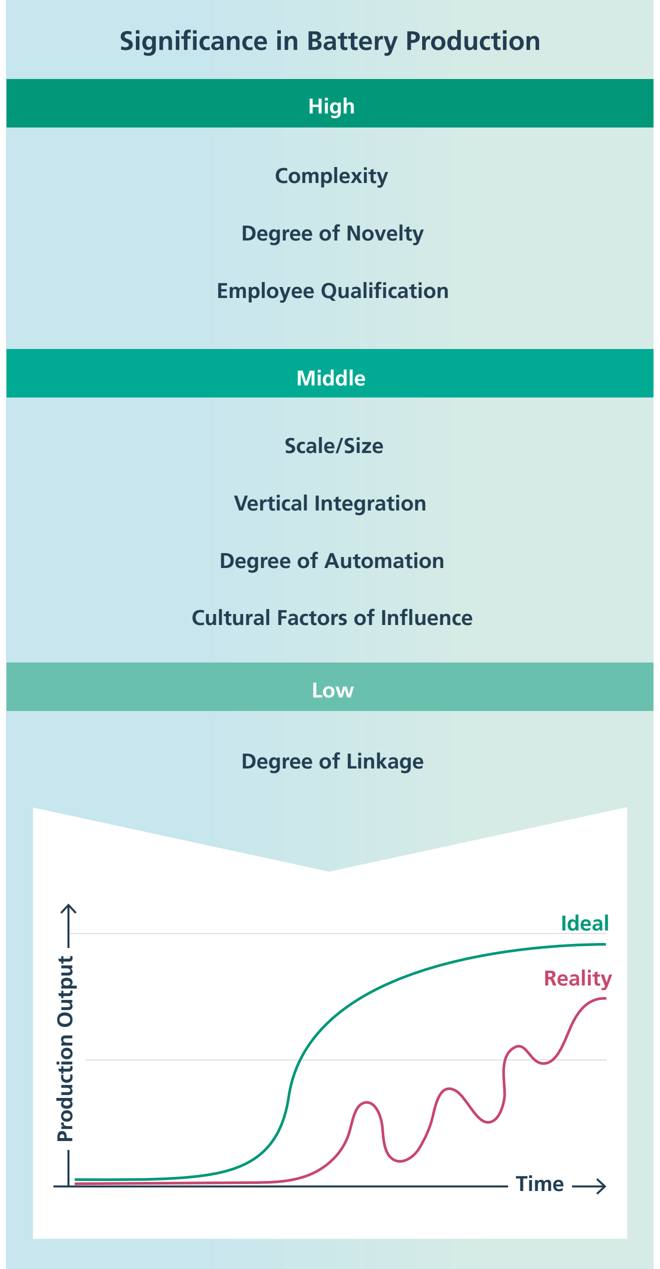


Figure 4 Influencing factors on ramp-up (in accordance with [2]).

The **scale** of a production facility also affects the complexity of ramp-ups. The size can be measured in terms of area, output, or the number of systems. These dimensions are particularly large in battery cell production. For instance, a gigafactory with an annual production capacity of 13 gigawatt-hours requires approximately 60,000 square meters of production space and more than 100 machines. This equates to approximately 440,000 cells (4680 cylindrical cells) being produced daily, which is sufficient to meet the annual demand of around 220,000 vehicles (Tesla Model Y standard range).

The **degree of automation** defines the ratio of processes which need manual interaction to those working solely on their own. This ratio is particularly high in battery production. Manual processes are only found in areas such as logistics or quality control but not in direct production processes in order to achieve the high output volumes required. This leads to an enormous demand for experts in the field of automation technology on the part of both cell manufacturers and suppliers. As can be seen with current European gigafactories, a shortage of such personnel poses a serious challenge.

The deployment of **qualified employees** or the upstream implementation of qualification measures is an important factor in the ramp-up phase, with the potential to shorten it accordingly. Errors and faults are identified and rectified at an early stage, and parameters are set correctly in a faster way. This is dependent on the general qualification, experience, and sufficient availability of appropriate personnel. However, it is anticipated that the battery cell production industry in Europe will be short of approximately 100,000 skilled workers by the year of 2030. The specific type of work which includes working in cleanrooms and drying rooms requires special skills and qualifications, making the start-up phase even more challenging.

The **degree of interlinking** of production processes also has a significant impact on ramp-up times. A high degree of interlinking results in a low level of flexibility, which means that if individual systems fail, upstream and downstream systems come to a standstill. As a potential solution, it is necessary to design and implement appropriate buffers to decouple the systems from each other. In battery cell production, interlinking is particularly high in assembly. A double-digit number of process steps is completed here, with the intermediate products being located on product carriers and the systems being interlinked.

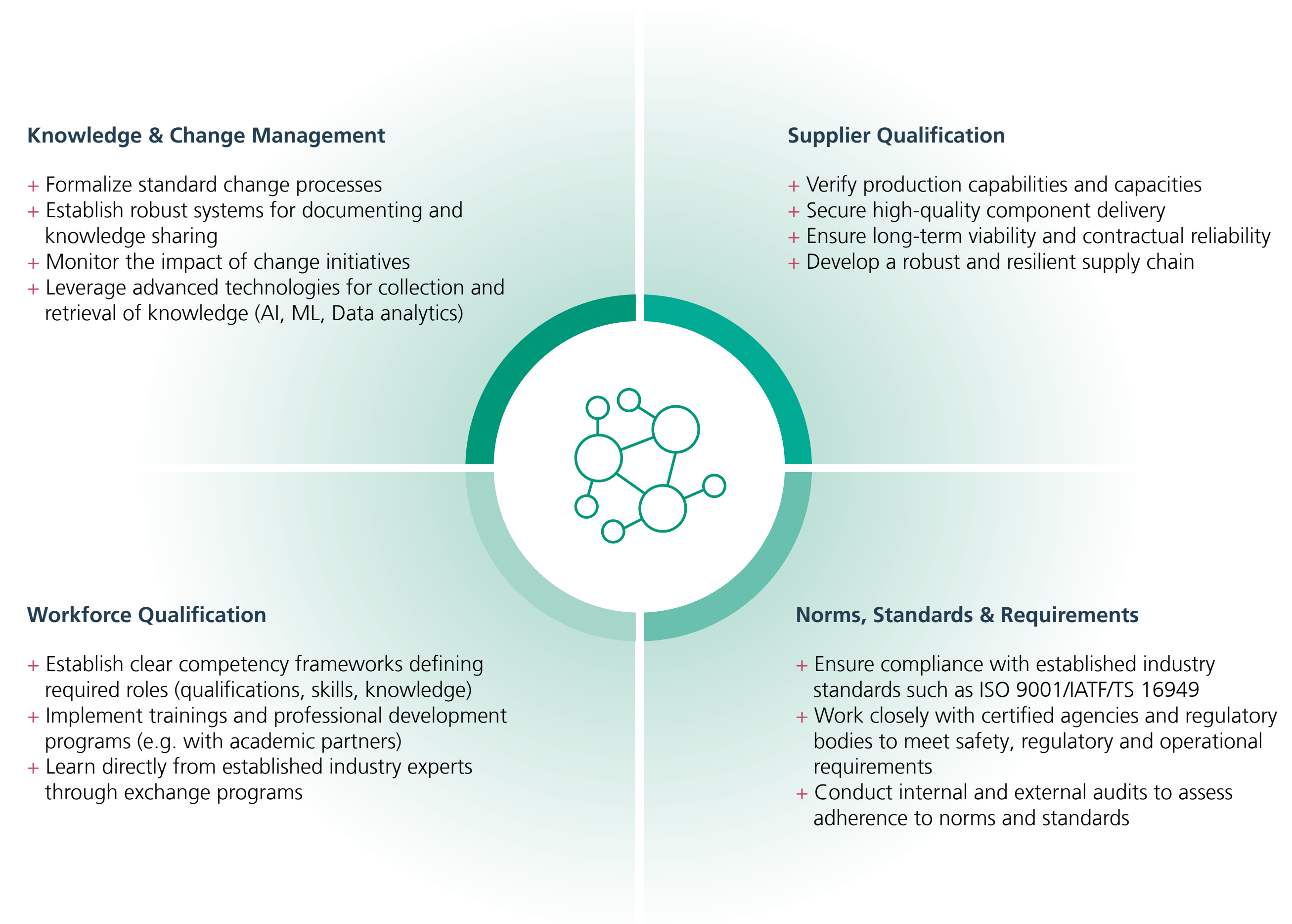
In general, increased **vertical integration** and in-house production of components reduces the number of suppliers, sub-suppliers, and external interfaces. This facilitates co-ordination and has a positive effect on the ramp-up. A large number of suppliers (for raw materials as well as machines and systems), as is the case in battery production, has a negative impact on ramp-up, as it increases dependency on suppliers. A battery cell usually consists of more than 20 components, assemblies, or raw materials that are sourced externally. Due to a lack of knowledge, the requirements for supplier components are currently often unreasonably high, which leads to non-acceptance and therefore delays.

Cultural and linguistic factors also significantly impact a ramp-up's effectiveness. Language barriers can impede the essential communication that is crucial to a process such as the ramp-up. Cultural differences, such as differing assumptions about responsibility or working time models, can also present obstacles. Most material suppliers, equipment manufacturers, and production experts specializing in battery cell production originate from Japan, China, and Korea. Cultural differences and language barriers can lead to misunderstandings and delays. It is therefore crucial to have sufficient internal expertise to bridge these gaps and ensure smooth collaboration.

This also applies to adjustments to systems as part of the ramp-up, as explained in the section on automation. The ramp-up process in battery cell production is influenced by a range of **technical and organizational factors,** leading to deviations from idealized progressions. Having presented the various factors influencing the difficulty of a production ramp-up and having demonstrated that many of these points apply to the ramp-up in battery cell production, we will now examine the specific challenges in greater detail, focusing on the areas of organizational and technical challenges.

3 Organizational Challenges

Overcoming organizational hurdles during the ramp-up phase is crucial for scaling battery production efficiently. Key challenges include upskilling the workforce, navigating supply chain complexities, driving change management, and adhering to strict industry standards (see Figure 5). Tackling these issues head-on, while making the most of existing knowledge and competencies within the organization, becomes a decisive factor for success.



Knowledge & Change Management

+ Formalize standard change processes
+ Establish robust systems for documenting and knowledge sharing
+ Monitor the impact of change initiatives
+ Leverage advanced technologies for collection and retrieval of knowledge (AI, ML, Data analytics)

Supplier Qualification

+ Verify production capabilities and capacities
+ Secure high-quality component delivery
+ Ensure long-term viability and contractual reliability
+ Develop a robust and resilient supply chain

Workforce Qualification

+ Establish clear competency frameworks defining required roles (qualifications, skills, knowledge)
+ Implement trainings and professional development programs (e.g. with academic partners)
+ Learn directly from established industry experts through exchange programs

Norms, Standards & Requirements

+ Ensure compliance with established industry standards such as ISO 9001/IATF/TS 16949
+ Work closely with certified agencies and regulatory bodies to meet safety, regulatory and operational requirements
+ Conduct internal and external audits to assess adherence to norms and standards

Figure 5 Key organizational challenges in battery factory ramp-up.

3.1 Knowledge and Change Management

Streamlining knowledge and change management is vital for keeping disruptions at bay during the ramp-up phase. Unexpected challenges or planning gaps that surface late in the process can trigger a domino effect, forcing adjustments not just to core components but also to interconnected systems, tooling, and even the entire supply chain. For instance, redesigning a component (such as a cell lid) may necessitate adjustments to adjacent components (like housing), production equipment (such as laser welding systems), and auxiliary tools (e.g., product carriers). To mitigate these risks, cell manufacturers need to foster a culture of knowledge sharing and initiative-taking change management. This involves creating mechanisms for the continuous transfer of expert insights and experiences across teams and departments. Establishing minimum maturity levels for components and designs ensures that only well-vetted and stable elements proceed to production, thereby reducing the likelihood of late-stage changes. Formalized standard change processes provide a structured approach to managing modifications. These processes should include clear protocols for evaluating the impact of changes, communicating them effectively to all relevant parties, and implementing them systematically. By doing so, organizations can ensure that changes are managed efficiently, reducing downtime, preventing costly errors, and maintaining production momentum.

3.2 Supplier Qualification and Management

Suppliers must not only be capable of delivering materials and components in the required quality and quantity but also be adaptable to production changes. The concept of boundary sampling plays a crucial role here, ensuring that all delivered components meet stringent quality requirements before being integrated into production. Close collaboration and continuous communication with suppliers are essential to maintain a stable and efficient supply chain while upholding the high standards of battery production.

Especially for battery production, the high standards necessitate rigorous monitoring and continuous improvement practices. Suppliers are often required to adhere to stringent environmental and safety regulations (e.g., sourcing electrode active materials), further complicating supplier management. By fostering strong partnerships and utilizing advanced quality assurance techniques, a battery gigafactory can ensure a reliable supply of high-quality components, which is essential for achieving production goals and maintaining product integrity. Quality assurance agreements are a key tool in managing suppliers, providing a framework to ensure that quality standards are consistently met throughout the supply chain. These agreements outline specific quality requirements as well as the testing and measurement methods required to verify compliance. Key components of these testing requirements often include detailed test criteria, frequency of testing and comprehensive specifications within the measurement plan.

A good example of the use of quality assurance (QA) agreements is the assurance of technical cleanliness for housing components or active materials in battery cell production. Here, cleanliness standards are critical to the overall performance and longevity of the final product. To manage suppliers effectively, it is essential to take a holistic approach that considers the overall capability of the supplier, particularly in relation to critical quality control points. This includes evaluating their performance against Incoterms and assessing potential transport risks. However, it is important to note that some sub-suppliers may agree to quality assurance terms for commercial reasons but may not have the capability to fully comply with these requirements. This could result in inferior quality and endanger industrialization targets within ramp-ups. Due eventual uncertainty in determining the effects of quality deviations on cell quality, newcomers in particular place exceedingly high demands on the quality of their suppliers' components (e.g. in terms of technical cleanliness). This creates enormous challenges even for suppliers, which could lead to quality problems and delays. Therefore, in addition to establishing QA agreements, it is equally important to qualify and train sub-suppliers to meet battery cell level requirements. By investing in sub-supplier capability development, manufacturers can ensure higher compliance rates and maintain desired quality standards throughout the production process. Additionally, realistic, and achievable requirement setting is fundamental.

3.3 Workforce Qualification

In the highly specialized and technical environment of a battery gigafactory, competence and preparedness of the workforce are critical to achieving a successful ramp-up. Employees need to be well-versed not only in the operational aspects of production equipment but also in the underlying principles of battery technology. This dual approach ensures that workers can effectively troubleshoot and optimize processes, leading to higher efficiency and quality in production. This requirement spans across various job functions, including operators, engineers, and project management staff, all of whom play an important part in maintaining high quality levels. The successful execution of a "Process Failure Modes and Effects Analysis" (P-FMEA) in accordance with automotive quality standards is a fitting example. This process demands that process engineers identify potential process failures and their corresponding causes, while quality engineers must develop suitable countermeasures, such as failure prevention or detection methods. FMEA moderators play a pivotal role by ensuring the correct application of FMEA methodology and maintaining accurate reporting to the customer. This complex interplay of responsibilities underscores the necessity for a targeted training program regarding the quality governance of the battery cell manufacturer. By implementing a comprehensive training program, a battery gigafactory can foster a well-informed workforce capable of effectively managing quality assurance processes and contributing to the overall success of the manufacturing operation.

Practical training on the production line is crucial for familiarizing employees with the specific machinery and workflows used in mass battery manufacturing. However, practical skills alone are not sufficient. Workers must also possess a thorough understanding of the chemical processes involved in battery production, such as electrode preparation, electrolyte handling, and cell assembly. This knowledge enables them to anticipate and mitigate potential issues that could arise from chemical interactions during production. Comprehensive training in safety protocols and emergency response procedures helps ensure a safe working environment, reducing the risk of accidents and ensuring compliance with regulatory requirements. The environmental conditions in battery cell production pose a further challenge when training employees. Large parts of electrode production take place under clean-room conditions. Cell assembly and parts of electrode production also take place under dry-room conditions. It must be ensured that production employees are trained to comply with the production conditions in order not to affect product quality. One specific example of this is compliance with the dew point. The drying room technology is designed for a specific operating point. A maximum number of people is assumed to be in the room at any given time. Those working in the drying room must be aware of this.

Due to its relatively early age, there is an acute shortage of experienced and skilled workers and production experts in the European battery industry. While this is especially challenging for new entrants into the battery market, even established manufacturers continue to struggle with transferring their knowledge from existing production facilities to newly established sites. Tailored offers in further education and training of workers are essential to combat this problem. However, it is also critical to support this effort by continually preserving the existing expert knowledge using dedicated knowledge management systems. Expert knowledge collected before and during the ramp-up phase must be stored in a suitable manner and made accessible on the shop floor through intuitive, user-facing software systems. Approaches for structured information representation for example, using knowledge graphs, enable an automated analysis of the stored information and can provide deeper insights into the production process.

3.4 Norms, Standards & Customer Requirements

Various standards, specifications, and customer requirements significantly influence the quality assurance of supplies, series ramp-up and its management. Relevant standards include, for example, ISO 9001 and the international IATF/TS 16949 standard for the automotive industry, which is based on it. These regulations are the results of collaborations among working groups from different companies, interest groups, and countries (e.g., VDA in Germany or AIAG in the US). Consequently, they contain the basic requirements agreed upon by these teams. The IATF 16949 entails a couple of further standards and automotive core tools such as APQP, PPAP, FMEA, MSA, and SPC that emanate further requirements towards the cell manufacturer. An example for the German market would be VDA 2, describing "Production Process and Product Approval" (PPAP). VDA Volume 2 "Quality Assurance for Supplies" outlines the fundamental requirements for sampling serial parts in the automotive industry. This standard ensures that suppliers understand and meet customer expectations, enabling the manufacture of products that achieve maximum customer satisfaction. Thus, the customer-specific requirements add another layer of complexity. OEMs may have additional specifications that exceed standard requirements, necessitating tailored quality assurance measures and customized production processes. Additionally, demands from technical purchasing and supply conditions, quality assurance agreements (QAA), or similar documents often align closely with previously mentioned standards, referencing them as supplementary documents and adapting as well as extending them to meet specific needs. These include, for example, requirements for an environmental management system according to ISO 14001 or the implementation of an eco-audit under EMAS.

> **»Ramping up battery cell production requires not only compliance with standards like ISO 9001 and IATF 16949 but also a tailored approach to meet the stricter specifications set by OEM customers. Effective collaboration among all stakeholders and sucessfully translating auto-motive requirements and other customer requirements to battery cell production is essential to ensure consistent product quality.«**
>
> **Hendrik Walter**
> Head of Department Strategic Corporate
> Development, Fraunhofer FFB

4 Technical Challenges

4.1 Overview of Technical Challenges across Battery Cell Production

In addition to the organizational challenges, there is an almost infinite number of technical challenges that need to be mastered. To approach the topic, Figure 6 shows a typical state-of-the-art production line as it is used in a contemporary gigafactory. Those facilities are made up of several such uniform lines to realize the corresponding production capacity. The process according to which the production output of the entire line is designed is usually the production output of the coating and drying process. The throughput of the upstream and downstream machines is designed based on the throughput of these two machines. Today's coaters have a coating speed of 60 to 80 meters per minute over a coating width of 1.5 to 2.0 meters. Depending on the cell chemistry, this allows seven to ten gigawatt-hours per year of electrode material to be produced.

There are challenges and sources of defects in each step-in battery production. However, there are production steps in which the risk of defects occurring is significantly higher than in other production steps. Figure 6 shows a heat map in which the risk of technical challenges or defects occurring is shown qualitatively along the production chain. The production steps that are crucial for battery cell quality or where defects are most likely to occur with a corresponding impact are the mixing, the coating as well as the separating and folding processes. In mixing and coating, the basic electrode is produced which is later processed and assembled to a battery cell. Thus, defects that occur here might affect subsequent production processes and therefore the battery cell quality at all. To illustrate this, in the following chapter we will demonstrate typical problems and defects which can occur during coating.

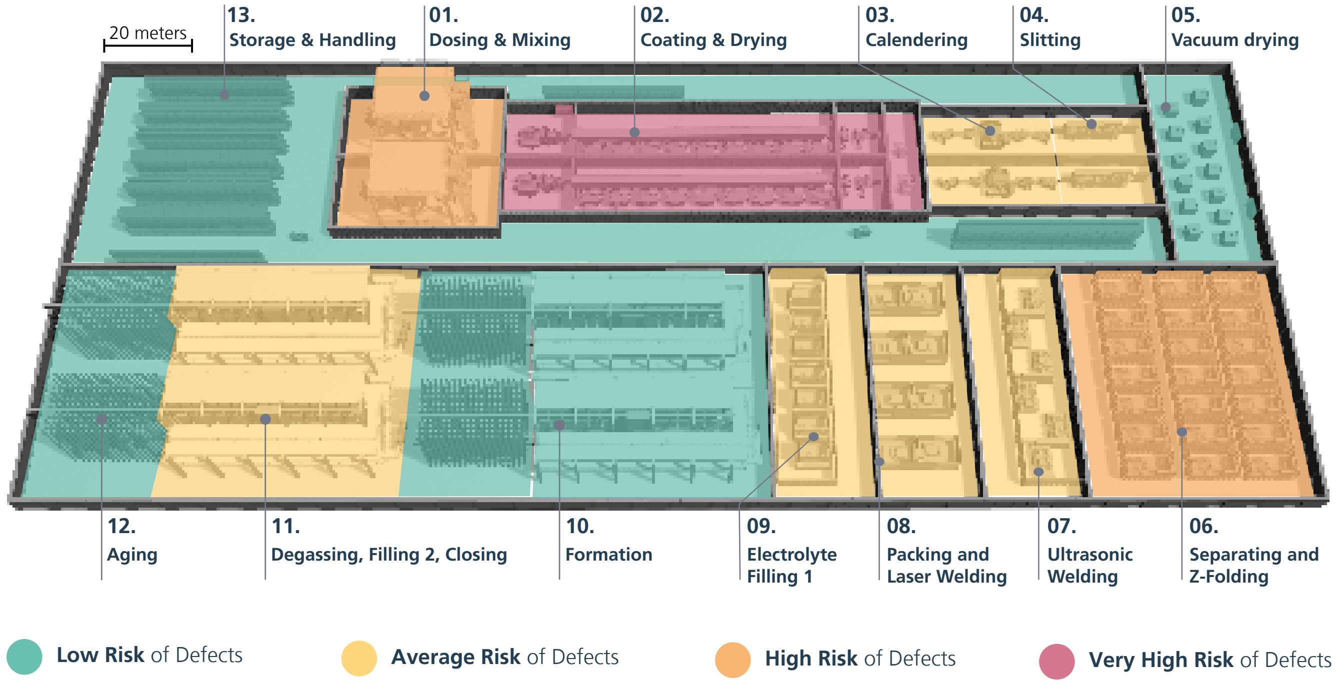


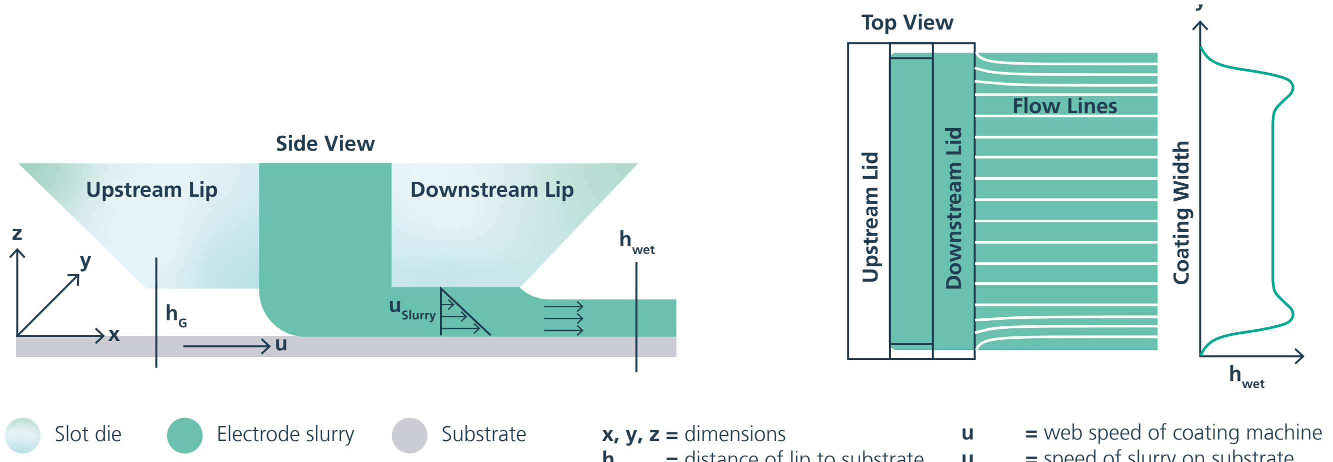
Figure 6 Layout of a typical, modular battery cell production line (7-10 GWh/a) and their risk level for defects. A battery cell factory has multiple of such modules/lines.

4.2 Example: Technical Challenges in Electrode Coating and Drying

In this section, the process step of coating is described in further detail, due to its high relevance regarding the final cell quality as well as the many challenges during ramp-up. However, as mentioned before, defects can occur in each step of battery production. Nevertheless, mixing and coating may be the processes of highest importance for quality.

In general terms: the key to profitable battery cell production is to optimize throughput (the number of cells produced per unit of time) and yield (the percentage of cells without defects). Ramp-up of coating and drying processes typically starts at low coating speeds to control the process as well as to save material and therefore costs. This coating speed is then gradually increased. The aim is to produce a coating film of uniform composition and thickness, with a defined residual moisture content, free of defects and with the top and bottom coating aligned as closely as possible. During this ramp-up, intense statistical calculations and methods are applied to ensure a high Overall Equipment Effectiveness (OEE) as well as the production of high-quality cells with low waste quantities. One of the main challenges of the coating process is to find the optimum overall parameter setting which secures a statistically dependable, defect-free production state at high web speeds (60 to 80 meters per minute). Electrode quality is sensitive to changes in process input parameters and input material quality, including slurry properties such as viscosity. Thus, it is essential to ensure that the incoming materials, the slurry, and substrate, have a constant quality and meet the requirements posed by the coating process. Consequently, between subsequent process steps, many iterations may be necessary to find a stable production state which also meets the quality targets for the final cells.

Another challenge is the coordination between the coating and drying parameters due to their inherent coupling. The necessity to adjust a multitude of process settings, including die-gap, die-angle, die-distance, pump-speed or pump-flow, and web-speed for the coater, as well as airflow and temperature for the dryer, introduces a considerable degree of complexity. With a closer look at the coating process, a quick deep dive into the adjustable settings may help to understand some of the major challenges and their inherent interfaces with previous and subsequent process steps. Figure 7 shows the flow of the slurry through the slot-die on the current collector in electrode coating. To coat a uniform electrode over a width of 1.5 to 2.0 meters, the slurry needs to be pumped with a uniform pressure and with as little pulsation as possible to the slot die. The geometry of the interior as well of the outlet of the slot die, the so-called lips, are essential for the quality of the coating film. Both need to be aligned to the properties of the slurry since different material compositions and viscosities result in different flow properties. On the right side of Figure 7, the white lines indicate the flow behavior after the slot die in web direction. Depending on the flow characteristics, edge formation may occur but needs to be avoided. However, this is just one simplified example of the many interactions of process equipment geometry, material composition and viscosity that needs to be understood and aligned in the electrode coating process to avoid defects and master the ramp-up.



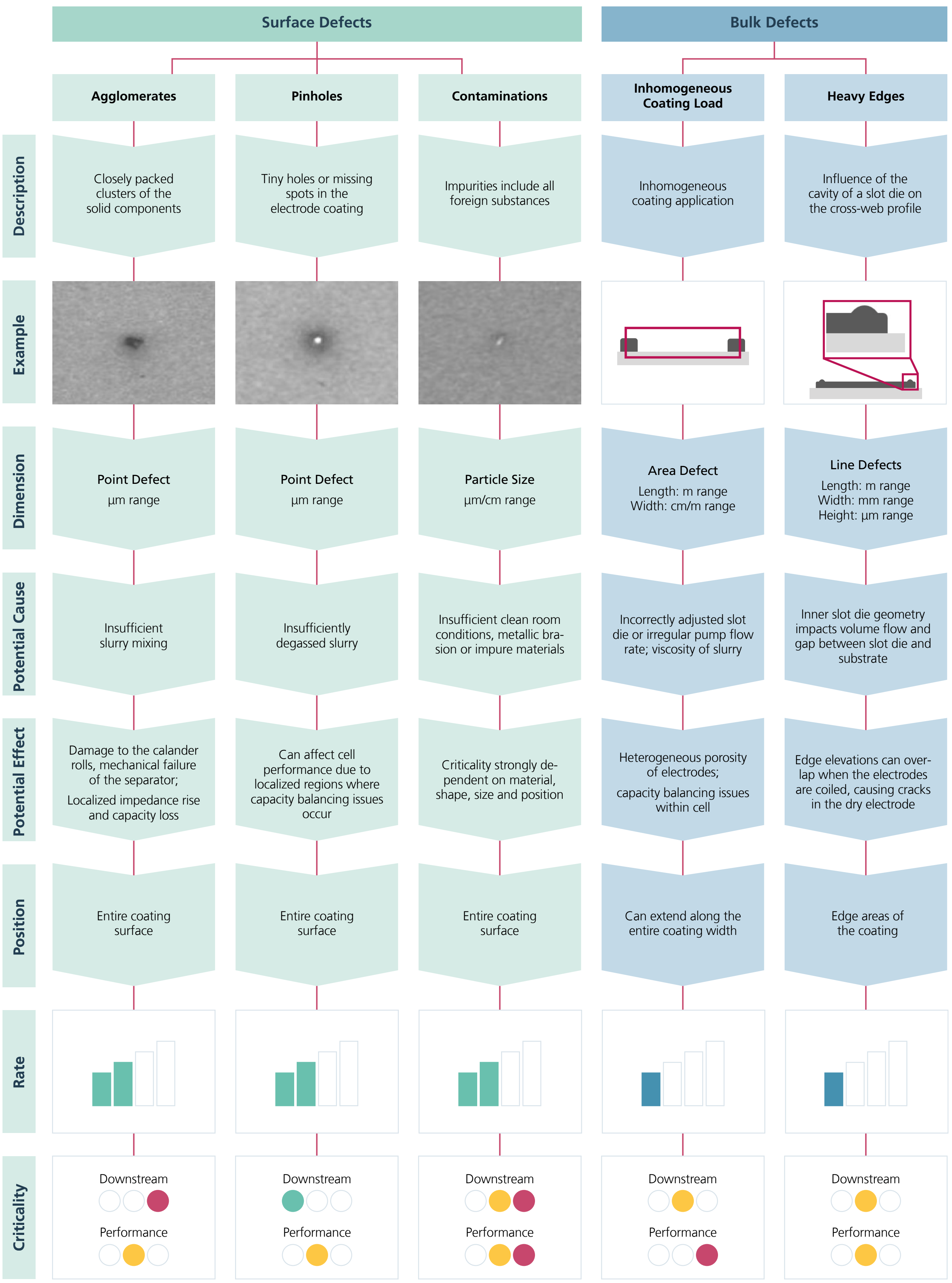
x, y, z = dimensions
h_G = distance of lip to substrate
h_{wet} = heigth of wet slurry
u = web speed of coating machine
u_{Slurry} = speed of slurry on substrate

Figure 7 Parameters in slot-die coating in battery electrode production.

A further major challenge occurs in the scale up of the coating process. In general, two ways of scaling are possible. One is to increase the width of the coating and thus the width of the coating machine which is represented by the y-axis in Figure 7. The second option is to increase the web speed of the coating machine, represented by "u" in Figure 7. Both increase the output of the process but results in multiple challenges due to non-linear cause-and-effect relations of the quality parameters. Furthermore, an increase in web speed also results in an increase in dryer length due to the shorter dwell time in the dryer per meter of electrode. Thus, the dynamics inside the dryer further influence the stability of the process and the quality of the electrodes produced. With an eye on the final product of the production line, the lithium-ion battery cell, independent from the format, the electrode is important for most of the major quality parameters and key performance indicators. A statistical relevant variance of the quality parameters defined in the coating process will result in a higher variance in cell-to-cell performance. This again describes the necessary maturity the complete process chain needs to reproducible manufacture similar cells of high quality: a feature that is crucial for the assembly of high-performance battery packs since a high cell-to-cell variance results in poor module and pack performance in both capacity and system voltage. Further challenges are the dimensions of the cell that need to be matched by the electrodes to be able to fit inside the housing and stay within the tolerances defined by the cell design. There, it is of high importance to be aware of the limitations of the installed process equipment since it defines the smallest possible tolerances. Furthermore, the most important quality features need to be monitored by reliable quality inspection systems. In many cases, the means of proving the maturity of these quality inspection systems is still subject to further research. VDA recently announced to publish a further issue especially on inspection systems since most audit systems for those inspection systems do not work properly. However, to further assess the errors that may happen during the production of a product, so-called error catalogs are an inevitable tool to be aware of what can happen and how to counter their occurrence. In Figure 8, an exemplary error catalog for the coating process is shown. In the catalog, all possible defects are listed, named and enriched with examples and potential causes. Furthermore, the criticality of each error is ranked downstream and with regard to the final cell performance. The main difficulty regarding the ramp-up process is either the set-up of an initial error catalog for new entrants in the market and the effect of these errors during the scale-up from pilot to gigafactory scale. Once the error catalog is in place and used at the machine, it will be a substantial part of the quality assurance measures on the shop floor for any battery gigafactory.

> »
>
> **The coating process is crucial for high-quality battery cells, as minor defects can affect subsequent production stages. To optimize throughput and yield, careful control of parameters like slurry viscosity and coating speed is essential, along with a thorough understanding of the underlying cause-effect relations. The complexity of coordinating coating and drying settings highlights the need for precision in production.«**
>
> **Markus Eckstein**
> Group Leader Electrode Production,
> Fraunhofer FFB

Defects Which Can Occur All The Time



	Surface Defects			Bulk Defects	
	Agglomerates	**Pinholes**	**Contaminations**	**Inhomogeneous Coating Load**	**Heavy Edges**
Description	Closely packed clusters of the solid components	Tiny holes or missing spots in the electrode coating	Impurities include all foreign substances	Inhomogeneous coating application	Influence of the cavity of a slot die on the cross-web profile
Example					
Dimension	**Point Defect** µm range	**Point Defect** µm range	**Particle Size** µm/cm range	**Area Defect** Length: m range Width: cm/m range	**Line Defects** Length: m range Width: mm range Height: µm range
Potential Cause	Insufficient slurry mixing	Insufficiently degassed slurry	Insufficient clean room conditions, metallic abrasion or impure materials	Incorrectly adjusted slot die or irregular pump flow rate; viscosity of slurry	Inner slot die geometry impacts volume flow and gap between slot die and substrate
Potential Effect	Damage to the calander rolls, mechanical failure of the separator; Localized impedance rise and capacity loss	Can affect cell performance due to localized regions where capacity balancing issues occur	Criticality strongly dependent on material, shape, size and position	Heterogeneous porosity of electrodes; capacity balancing issues within cell	Edge elevations can overlap when the electrodes are coiled, causing cracks in the dry electrode
Position	Entire coating surface	Entire coating surface	Entire coating surface	Can extend along the entire coating width	Edge areas of the coating
Rate	▮▮▯▯	▮▮▯▯	▮▮▯▯	▮▯▯▯	▮▯▯▯
Criticality	Downstream ○○🔴 Performance ○🟡○	Downstream 🟢○○ Performance ○🟡○	Downstream ○🟡🔴 Performance ○🟡🔴	Downstream ○🟡○ Performance ○○🔴	Downstream ○🟡○ Performance ○🟡○

Figure 8 Defects which might occur during coating and drying of battery electrodes.

Once an operator encounters something that looks like the examples in the error catalog, the further columns of the respective error may help in either understanding the potential causes and effects as well as the criticality for the quality downstream of the respective electrode and the final cell performance. Additionally, we assess how each error impacts the performance of the ramp-up. With this information readily available near the machine, we can provide immediate guidance and support. For example, we detail error No. 6, known as "heavy edges," along with an image. We also outline potential causes and effects, helping operators determine whether the affected electrode can be reused.

With digital traceability tools in place, we can pinpoint the error and trace it back to the relevant process, allowing us to isolate it from production. Moreover, operators can enhance the digital error catalog by adding missing errors and suggesting solutions based on their experiences with the effectiveness of these approaches. This collaborative effort helps create a more comprehensive resource for error management. In summary, the process of ramping-up battery cell production from laboratory to mass production involves several complex challenges, including equipment scaling and process parameter tuning. The level of automation and the interdependencies of the various process parameters add to the overall complexity. Overcoming these challenges requires a thorough understanding of the processes involved, as well as expert knowledge and a structured approach to ensure a successful ramp-up and optimization of the production process.

4.3 Digitalization Challenges

A full digital integration of all machines and the building infrastructure has become increasingly relevant and a prerequisite for many other technologies and use cases. Only with this digital integration and a traceability system can we adequately monitor the production line, utilize data-driven methods for product and process optimization, and support employees at all levels by providing and visualizing valuable information. This comprehensive approach enhances decision-making and operational efficiency throughout the organization. Digitalization of a battery manufacturing plant offers high potential but comes with high implementation efforts and its own challenges [3].

As a first step toward a digitalized factory, we need to implement a suitable architecture that includes a Manufacturing Execution System (MES), Enterprise Resource Planning (ERP), a robust database management system, and an Industrial Internet of Things (IIoT) platform. This integrated approach lays the foundation for streamlined operations and effective data management. For the MES and ERP, this means providing the framework for all current and future organizational and production processes, such as managing production orders, traceability functions as well as planning maintenance. The IIoT platform, on the other hand, needs to connect hundreds of sensors and the productions machines with thousands of data points while staying manageable, usable, and well organized. It also needs to be set up in a flexible and adaptable way to be able to include future changes such as new productions lines, additional measurement systems, and new products. A lack in flexibility and adaptability can lead to the inability to include necessary future changes in the production line, which then causes the need for a new IT architecture or the necessity of running two parallel systems. Adaptability is especially important in the battery manufacturing industry where innovations on product and process levels come at a fast pace. Furthermore, all different IT systems need to be seamlessly integrated and connected to enable automated data transfer and avoid a loss of information. The selection and launch of the IT architecture involve various stakeholders, including production planners, machine and sensor vendors, and shop floor staff. It's essential to coordinate these efforts with the overall strategy to avoid standalone systems that lack automated connections. While the initial set up is labor-intensive, if done right it can significantly reduce maintenance and labor later and enable many beneficial use cases and optimization methods.

Since reliable data from the shop floor is a key enabler for an efficient and targeted ramp-up, the digital integration of assets in the ramp-up's initial stages is critical. However, as shown in Figure 9, different asset and software vendors frequently use varying data descriptions and communication protocols that are often not fully compatible with each other. This leads to inconsistent parameter naming, differing units, and general incompatibilities between systems, causing additional manual overhead for translation and integration of the production systems. Typically, this work needs to be conducted at a time when the corresponding teams should focus on utilizing the collected data to support the actual commissioning of the assets.

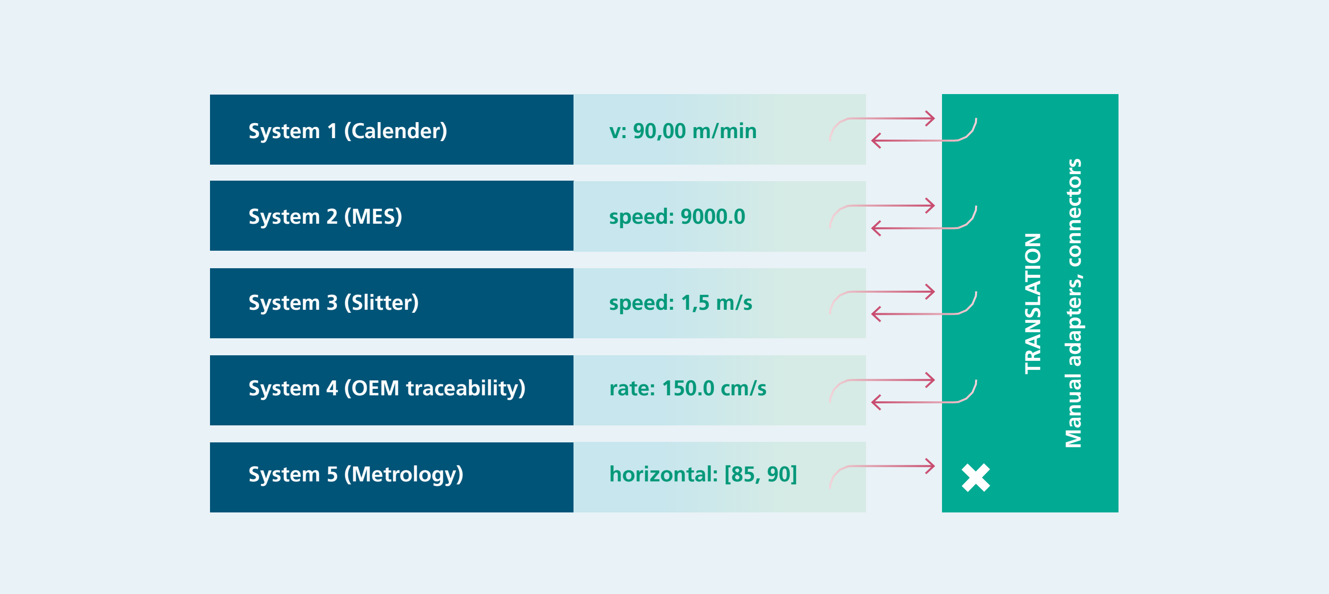


Figure 9 Example of different parameter names and units used by different systems.

The asset onboarding problem becomes particularly relevant each time a new asset, component, or subsystem is replaced or introduced into the production system. In most cases, novel solutions must be custom developed, which often cannot be reused for future components. This not only leads to delays from manual implementation efforts but also increases the likelihood of errors, such as incorrect unit conversions or data type mismatches, which can cause data loss or system malfunctions. These issues have the potential to delay the entire ramp-up process.

In battery cell manufacturing, the production process is overly complex, involving many interdependencies and cause-and-effect relationships (CERs). The challenge lies in identifying these CERs and optimizing production parameters. Traditional methods like optimization and Design of Experiments (DoE) can address these challenges, but they tend to be time-consuming and resource intensive. More efficient approaches, such as data analysis, machine learning (ML), and artificial intelligence (AI), offer solutions, but they come with their own set of challenges. One of the primary issues with using data-driven approaches is the need for traceable data that can be mapped to the final product throughout a production process, which includes both discrete and continuous steps. Additionally, the high dimensionality of the data space – stemming from numerous parameters, external factors, and time series – requires a large volume of data to establish statistically significant CERs. However, during the initial ramp-up of a production line, data is often scarce, creating a "chicken-and-egg" problem: data is needed to optimize production, but production must be running to generate that data.

Lastly, the time lag between conducting experiments, analyzing the results, and incorporating new insights into the next phase of experiments further exacerbates the inefficiency. Noteworthy events, whether positive or negative, might not be detected immediately, leading to poorly informed planning and longer ramp-up times.

In summary, the key challenges of digitalization during the ramp-up phase are:

- **Coordination of Stakeholders:** A large number of stakeholders must be aligned, each with unique needs, leading to complexity in managing various tasks that IT systems must address.
- **Lack of Standardization:** The absence of standardized protocols increases the implementation effort required to integrate machinery and sensors effectively.
- **Rapid Industry Changes:** The fast pace of change and uncertainty regarding future developments in the industry pose significant challenges for planning and adaptation.
- **Data Scarcity:** Limited data availability at the onset of the ramp-up process hampers effective decision-making and optimization efforts.

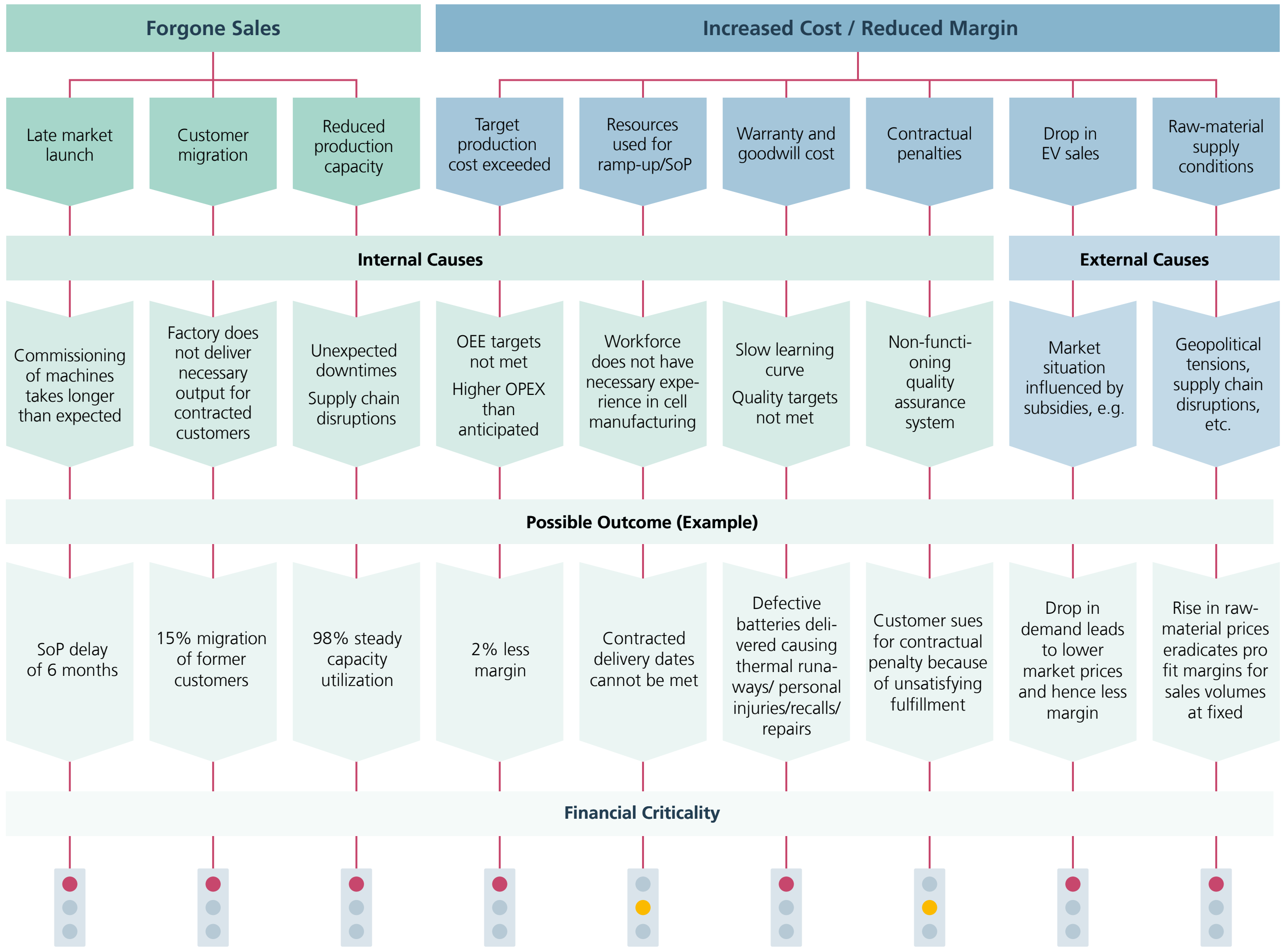
5 Financial and Time Consequences

The ramp-up phase in battery cell production is crucial for the project's overall viability. This stage carries significant risks that, if not effectively mitigated, can lead to underutilization, delivery delays, quality issues, and ultimately financial underperformance. Numerous European projects have faced delays, postponements, or even cancelations. On average, these delays amount to approximately seven months or longer [5]. This period, characterized by high cash burn, jeopardizes the success of many projects, potentially leading to failure. The recent example of Northvolt shows which consequences a suboptimal ramp-up can have. Northvolt was not able to deliver their cells in the desired quantity and time, which led to customer migration and the cancellation of BMW's major order worth approximately two billion euros. Such setbacks underscore the risks associated with the ramp-up procedure. [6,7]

The implications and financial consequences of ramp-up difficulties, shaped by technical and organizational factors described above, are diverse. The financial consequences can be categorized into forgone sales and increased cost or reduced margin, each due to internal causes related to ramp-up problems or additional external factors. Figure 10 offers an overview of these factors leading to different possible outcomes and their financial criticality to the project itself, which is assessed qualitatively.

The consequences shown in Figure 10 can be divided into internal and external causes. These are explained below:

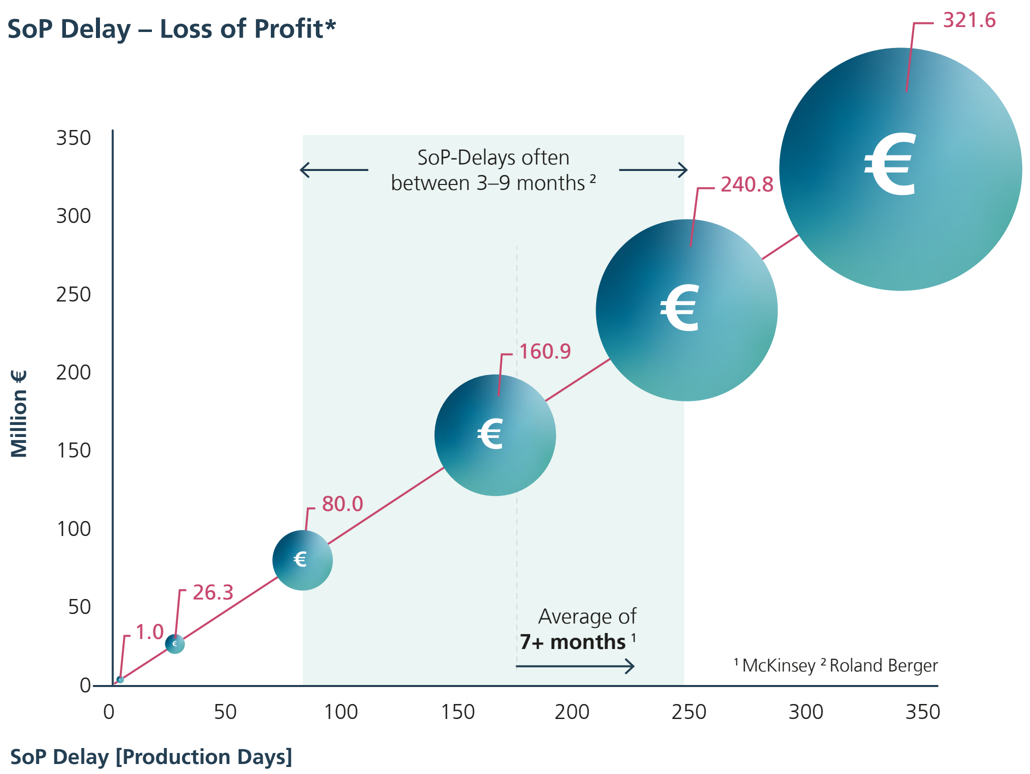
Financial Consequences



Forgone Sales			Increased Cost / Reduced Margin					
Late market launch	Customer migration	Reduced production capacity	Target production cost exceeded	Resources used for ramp-up/SoP	Warranty and goodwill cost	Contractual penalties	Drop in EV sales	Raw-material supply conditions
Internal Causes							External Causes	
Commissioning of machines takes longer than expected	Factory does not deliver necessary output for contracted customers	Unexpected downtimes Supply chain disruptions	OEE targets not met Higher OPEX than anticipated	Workforce does not have necessary experience in cell manufacturing	Slow learning curve Quality targets not met	Non-functioning quality assurance system	Market situation influenced by subsidies, e.g.	Geopolitical tensions, supply chain disruptions, etc.
Possible Outcome (Example)								
SoP delay of 6 months	15% migration of former customers	98% steady capacity utilization	2% less margin	Contracted delivery dates cannot be met	Defective batteries delivered causing thermal runaways/ personal injuries/recalls/ repairs	Customer sues for contractual penalty because of unsatisfying fulfillment	Drop in demand leads to lower market prices and hence less margin	Rise in raw-material prices eradicates profit margins for sales volumes at fixed
Financial Criticality								
🟥	🟥	🟥	🟥	🟨	🟥	🟨	🟥	🟥

Figure 10 Potential causes and effects on financial performance through internal (ramp-up-related) and external causes.

SoP Delay – Loss of Profit*



*** Assumption Production Scenario:**
40GWh/a; NMC811 pouch cell; location: Germany; 330 production days per year

Figure 11 Loss of profits depending on SoP delay [days].

Internal causes related to ramp-up problems: Reduced production capacity due to inefficiencies leads to higher product costs, mirroring the effects of delays. Lower utilization rates result in higher costs per unit, affecting the overall profitability and economic viability. The aim is therefore to achieve the steepest possible ramp-up curve so that ongoing costs such as depreciation of machinery and buildings can be offset as quickly as possible by sales proceedings.

Low quality and defective batteries pose a significant risk, potentially leading to thermal runaways that can cause personal injuries, recalls, and repairs. These issues result in increased warranty and goodwill costs. Furthermore, if the overall quality does not meet customer expectations, it can tarnish the company's image and lead to customer migration. Also, a high scrap rate in production results in higher operating expenditures and ultimately higher production costs.

SoP delays result in a later market launch, causing potential shortages in delivery. This not only risks contractual penalties but can also lead to customer migration. Moreover, prolonged ramp-up phases increase production costs. For a modeled hypothetical battery cell factory with a 40-gigawatt-hour capacity producing NMC811 cells, the financial decline due to SoP delays is significant, averaging around 1.1 million euros per day. Delay periods typically range from three to nine months, with an average delay exceeding seven months, as illustrated in Figure 11. These prolonged delays can result in substantial financial losses. For example, a seven-month delay could lead to a potential loss of profit exceeding 160 million euros in this specific scenario. This figure primarily considers the missed market opportunity. Potential contractual penalties and reduced margins due to increased production costs would further worsen the financial result.

External causes: The financial performance of battery cell production ramp-up projects is also affected by various external factors, such as the market situation for electric vehicles and raw materials.

A decline in electric vehicle (EV) sales directly translates to **weaker demand** for battery cells. This decrease in demand forces manufacturers to lower sales prices to remain competitive, which in turn reduces profit margins. The subsequent decline in profits can severely impact the project's financial stability, making it more challenging to sustain operations and meet financial targets during the critical ramp-up phase. Slower than expected growth in EV sales and cumulative announced gigafactory projects exceeding actual demand may lead to the risk of underutilization. [8]

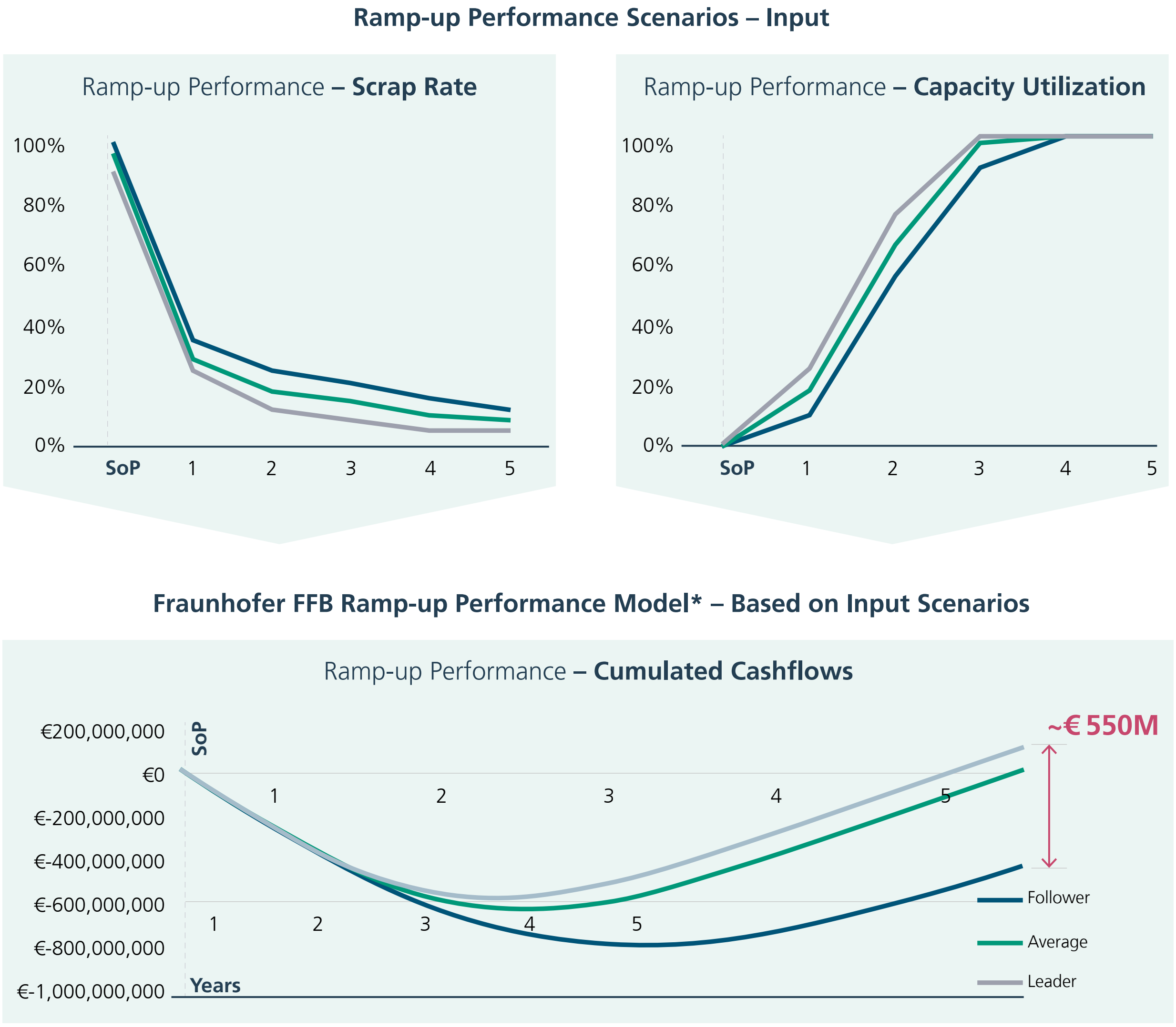
The conditions surrounding raw materials are another significant external factor affecting financial performance. Supply chain issues, such as disruptions in the availability of essential raw materials, can lead to production delays and increased costs. Additionally, fluctuating prices of raw materials add another layer of financial uncertainty. When prices spike unexpectedly, the cost of production rises, squeezing profit margins even further. Conversely, if prices drop, competitors with an aggressive pricing strategy could prioritize market share instead of profits which puts pressure on lowering sales prices and smaller profitability, as recently observed in China [9].

Delays in ramp-up extend the period of high fixed costs and low revenue generation, while high scrap rates increase variable costs and reduce the effective output. Together, these factors can postpone the break-even point, requiring additional financial resources to sustain operations until profitability is achieved. In order to ensure an optimal ramp-up, additional financial resources must be made available for personnel expenses and ramp-up task forces. Cell manufacturers have to be aware of this trade-off and must carefully compare expenditures with the benefits to achieve an overall economic optimum.

Two critical parameters during the ramp-up phase are the scrap rate and the utilization of full production capacity. Optimizing these parameters can significantly influence a ramp-up's economic viability and success. Figure 12 shows an example of the impact on the overall financial performance with different scenarios (follower, average, and leader) being assumed for the learning curves regarding scrap rate and capacity utilization.

Know your numbers!

In-depth knowledge about the financial consequences of different ramp-up performances is crucial. Especially for market newcomers, it is important to reach an early break-even point and become profitable to increase attractiveness for investments and secure further funding initiatives. The construction of a factory can be successful, but the survival of the project is assured in the ramp-up phase.



*** Assumption Production Scenario:**
40GWh/a; NMC811 pouch cell; location: Germany

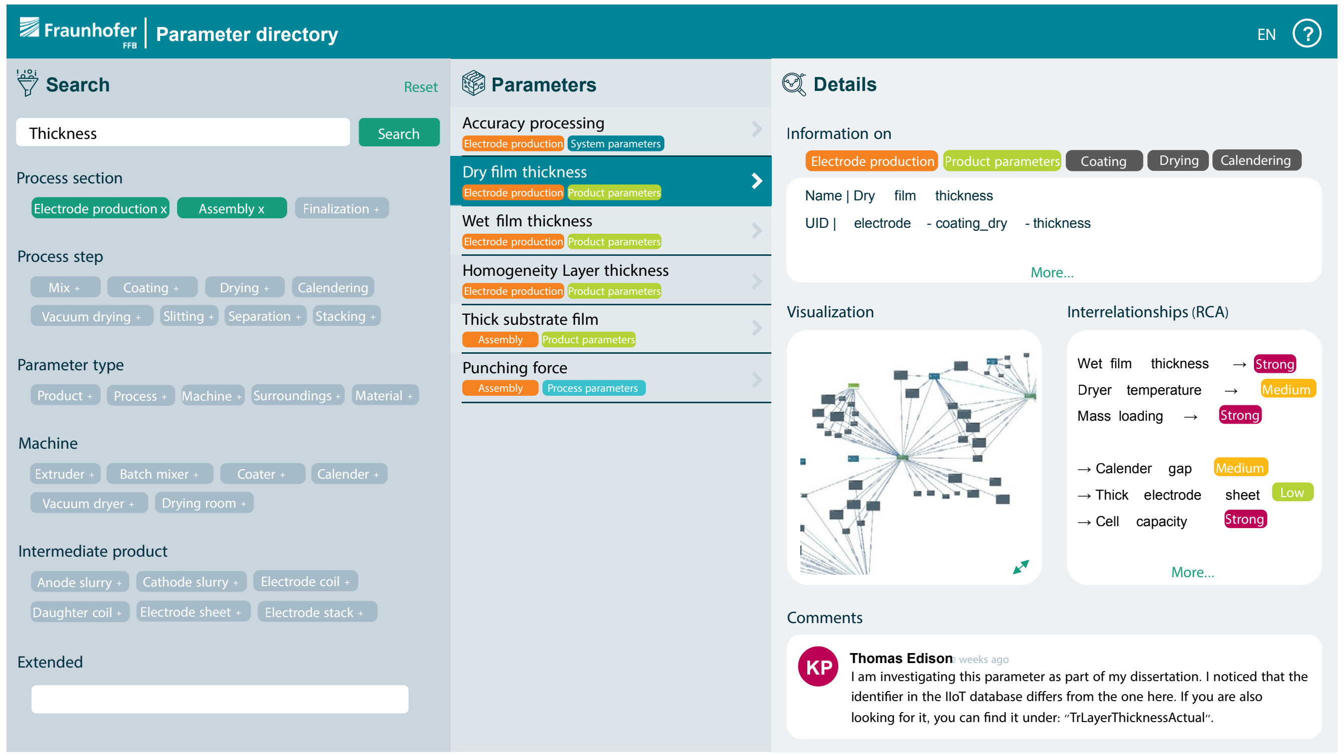
Figure 12 Financial performance (cumulated cashflows) based on different ramp-up performance scenarios (follower, average, leader).

When utilization and scrap rate curves are not optimized, the break-even date – meaning the point at which cumulative revenues equal cumulative costs – can be significantly stretched over years, as illustrated by the exemplary modeling exercise in Figure 12. In the scenarios analyzed, an improvement in performance can quickly lead to a span in cumulative cash flow in the three-digit million range. This illustrates how the performance in the ramp-up phase has a strong impact on the overall economic situation.

6 Ways, Methods, and Tools to Reduce Ramp-up Time and Cost

6.1 Overcoming Organizational Challenges

In Chapter 3, an excerpt from all the organizational challenges a battery cell manufacturer may face were briefly outlined. Challenges were divided into the four dimensions of "Knowledge and Change Management", "Supplier Qualification and Management", "Workforce Qualification", and those regarding "Norms and Standards". Effective strategies to manage the multitude of the organizational challenges hiding behind those dimensions is essential to secure successful ramp-up, while paving the way forward for continuous improvement and highest quality in production. Together, Fraunhofer FFB and PEM of RWTH Aachen University have developed numerous tools designed to address these challenges and support organizations in navigating the complexities of battery cell manufacturing. Addressing the field of knowledge and change management, one of the primary tools developed is a comprehensive knowledge transfer framework that ensures critical information is effectively shared across all levels of the organization. This framework includes structured training programs, digital knowledge repositories, and continuous learning platforms, all aimed at minimizing knowledge gaps and enhancing the adaptability of the workforce to evolving technologies and processes. A key element within this framework is access to a large-scale infrastructure for battery production research, which enables project-specific and practical production trials. These trials experiment with varying input materials, process setups and production volumes, providing insights and experiences that can be directly utilized for efficient pre-validation. To ensure that production expertise remains usable and easily accessible, digital methods are typically employed. Digital tools can capture and categorize specific knowledge, linking it to products, machines, components, or process steps. Information thereby can be documented in various formats ranging from instructions, videos up to basic checklists, serving as a valuable resource for a broader range of employees. Presenting this knowledge in a targeted and demand-driven manner becomes essential for maximizing its effectiveness. At Fraunhofer FFB, the complex interdependencies between process and quality parameters in linked process steps are stored by using a graph database. This allows for a weighted representation of the cause-and-effect relationships which can then be traced throughout the process. Initially, these weights can be set by experts and consecutively be validated or refuted by root cause analysis and data-driven methods, as described in Figure 13. It shows FFB's approach to visualize parameter interdependencies on the shop floor. The systems allow operators to capture lessons learned and feedback directly at the shop-floor level to systematically store and leverage knowledge later on.



Thickness

Name | Dry film thickness
UID | electrode - coating_dry - thickness

Wet film thickness → Strong
Dryer temperature → Medium
Mass loading → Strong

→ Calender gap Medium
→ Thick electrode sheet Low
→ Cell capacity Strong

Thomas Edison 2 weeks ago
I am investigating this parameter as part of my dissertation. I noticed that the identifier in the IIoT database differs from the one here. If you are also looking for it, you can find it under: "TrLayerThicknessActual".

Figure 13 Fraunhofer FFB UI to explore parameters, connections between parameters, and all related information.

As pointed out, **supplier qualification and management** likewise are of immense importance in ensuring reliable battery production. A thorough understanding of how to assess and quantify production materials becomes essential for ensuring stable and robust production. Efforts should therefore be directed towards setting realistic and necessary quality requirements for suppliers. Providing detailed specifications for all battery components, potential issues can be identified and mitigated early before they impact production. For instance, maintaining stringent cleanliness levels for battery components is essential, as these directly affect product quality and process capability. Achieving this requires close collaboration with suppliers to set appropriate limits, such as for particle contamination and to select the right packaging materials and methods to ensure contamination-free delivery to the production line. Regular audits, performance evaluations, and establishing close feedback loops with suppliers further enhance the ability to address such issues quickly.

One of the most significant challenges for entrants into the European market within the lithium-ion battery (LIB) value chain is the **availability of trained personnel/workforce.** Addressing this issue requires a strategic approach to specialized training that fills skill gaps and provides comprehensive education for operators, scientists, and management. Identifying training requirements for distinct roles within gigafactories is crucial. For example, production and quality engineers need battery-specific knowledge, including product details, production processes, and quality standards. In contrast, shop floor operators need training on proper conduct and procedures for working in cleanrooms and drying rooms, as well as foundational training on workplace safety and guidelines for the safe handling of lithium-ion batteries. Therefore, developing tailored training programs, leveraging industry partnerships for skill development, and investing in continuous professional education all become effective strategies to ensure that the entire workforce is well-equipped to meet the special demands in battery production. Additionally, collaborating with educational institutions and industry organizations can help create a pipeline of skilled workers and keep the workforce updated with the latest advancements in battery technology.

Finally, when focusing on the establishment and operation of European production facilities, navigating regulatory and methodological standards becomes crucial to meeting various **norms, standards, and requirements.** To tackle these challenges effectively, companies often implement structured approaches to regulatory compliance, including thorough engagement with relevant standards and collaboration with industry experts. An example of this is the CE marking according to the EU Machinery Directive, which is not merely a formality but a fundamental requirement to ensure that the machinery adheres to stringent European Union standards. Especially in the context of battery production, where processes often involve hazardous materials and high-energy components, ensuring that machinery meets these safety standards is vital to protecting workers from accidents and unacceptable health risks. Additionally, adopting robust internal audit systems can ensure adherence to regulations and highlight areas for improvement. Establishing clear communication channels with regulatory bodies and participating in industry forums can also provide valuable insights into evolving standards and best practices. By proactively managing these aspects, improved alignment with regulatory expectations and thus operational efficiency is possible.

6.2 Overcoming Technical Challenges

As detailed in the examples shown in Chapter 4, battery production, particularly during the ramp-up phase, presents cell manufacturers with a multitude of technical challenges. One of the primary challenges involves managing the complex interdependencies between process and quality parameters across interconnected process steps. This complexity makes it difficult to determine clear cause-and-effect relationships, therefore requiring expert knowledge and data-supported methods.

Experience from previous projects in ramp-up management indicates that by an early and systematic maturity level management, many issues may be anticipated before they arise, effectively preventing their occurrence during the critical ramp-up phase. Fraunhofer FFB and PEM of RWTH Aachen University possess the necessary expertise to support the product life cycle from the early development stages, employing established methods for operational guidance, as shown in Figure 14.

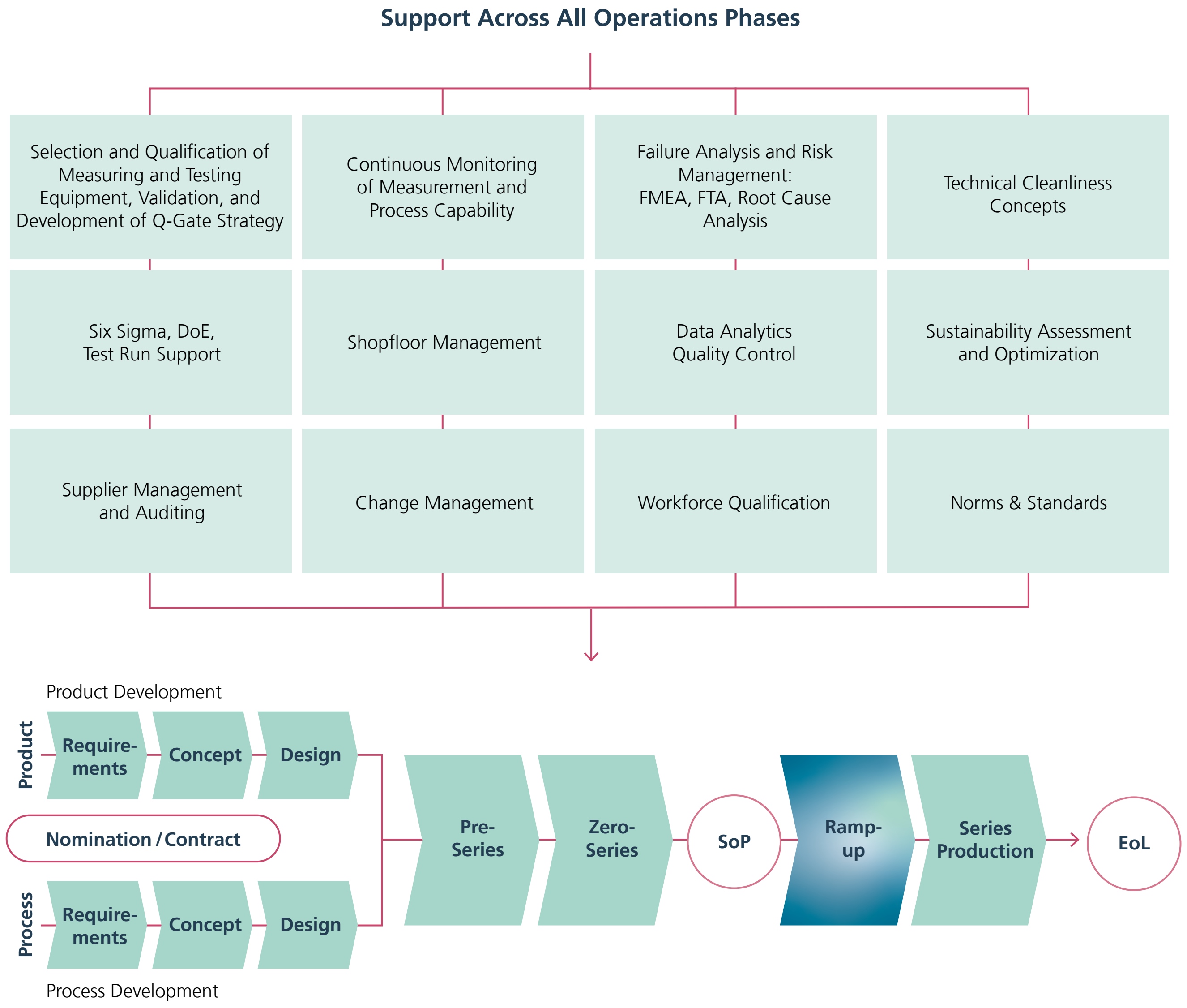


Figure 14 Fraunhofer FFB and PEM support expertise alongside the product life cycle.

Experienced troubleshooting throughout the production ramp-up is pivotal for identifying the root causes of production issues, leading to smoother operations with less downtime and optimized production processes. Performing proper troubleshooting thereby relies on a systematic approach such as the root cause analysis (RCA), which is paramount to get to the underlying reasons for faults or problems. Addressing the root causes then helps to prevent the recurrence of the same issues, contributing to the long-term stability and reliability of the production process. Successful execution and implementation of RCA significantly benefit from deep battery expertise, particularly regarding product-process interdependencies along the process chain. This is critical because the root causes of issues can be embedded early in the process due to complex interactions and may only become apparent later. However, in-depth battery expertise already aids by clearly describing and delineating the problem right at the beginning of RCA and capturing relevant data (e.g., measurement logs, frequency, and timing of quality issues, etc.). Such a clear understanding of the problem at the outset then forms the basis for identifying the multitude of potential influencing factors, analyzing their impact on the existing problem and prioritizing interventions and solutions. As an example, a common issue during ramp-up might be deviations in coating weight, a critical product characteristic affecting final cell properties such as total capacity and energy content. An RCA (see Figure 14) methodically breaks down possible influencing factors across several core dimensions, facilitating the systematic investigation of potential root causes.

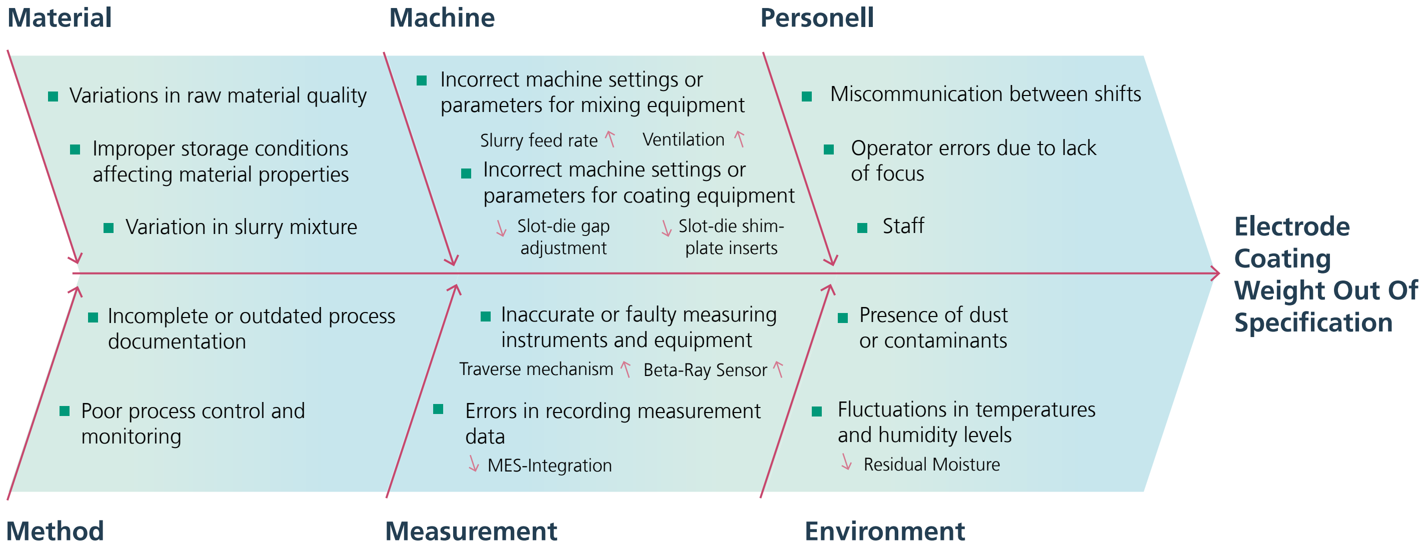


Figure 15 Ishikawa-Diagram analyzing deviations in electrode coating weights.

The analysis shows that in addition to varying material properties due to possible process changes at the suppliers, incorrectly set process parameters and inexperienced or untrained personnel, many other aspects can contribute to the problem. This root cause analysis forms the basis for efficient troubleshooting, then leading to actions such as inspection of equipment calibration, examination of maintenance protocols, review of process parameters, analysis of measurement tools and methods, or even checking environmental factors such as historic data on temperature and humidity levels. Once the root cause is identified, corrective actions can be derived and implemented. This may mean adjusting equipment settings together with process parameters, improving material handling and storage concepts, or providing additional training to operators. In addition to understanding the cause-and-effect relationships, the measures must be selected to suit the temporal context. Figure 15 provides an overview of suitable measures to ensure quality in the ramp-up process.

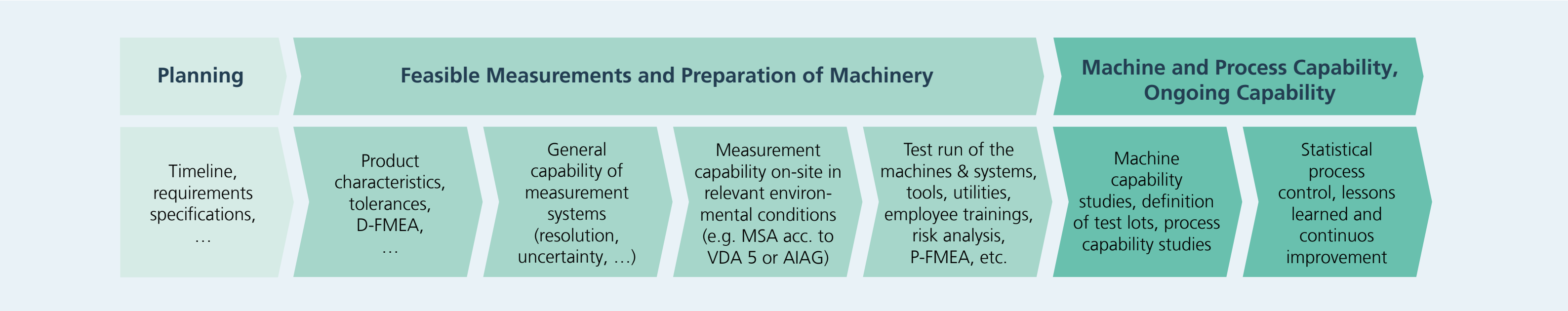


Figure 16 Overview of suitable measures to ensure quality in the start-up process.

During the initial planning phase, the timeline, requirements, and specifications are determined. For the preparation of machines, firstly product characteristics and tolerances are complemented by conducting Design Failure Mode and Effects Analysis (D-FMEA) to anticipate and mitigate potential issues. Furthermore, the general capability of measurement systems, considering factors such as resolution and uncertainty, should be evaluated. Afterwards, they should be assessed on-site in relevant environmental conditions, according to standards like VDA 5 or AIAG. Test runs of machines and systems represent the end point of the preparatory work, incorporating necessary tools, utilities, employee training, and risk analysis, along with a Process Failure Mode and Effects Analysis (P-FMEA).

To ensure machine and process capability in an ongoing production environment, two measures are critical. This includes the definition of test lots to evaluate specific machine functions under controlled conditions and performing process and machine capability studies to ensure that the production process can consistently meet required standards. Leveraging statistical process control, lessons learned, and continuous improvement initiatives marks the last step in maintaining high quality in ramp-up operations. Mastering the precise coordination and targeted use of these instruments enables Fraunhofer FFB together with PEM of RWTH Aachen University to achieve a very high level of quality in the ramp-up phase.

6.3 Overcoming Digitalization Challenges

As mentioned in chapter 4.3, digitalization offers many opportunities but comes with challenges and potentially high implementation costs. In the following, we will look at ways to reduce the implementation costs and methods to maximize the benefits.

In a first step, the IT architecture, including the IIoT platform and the MES, needs to be set up. As mentioned in chapter 4, these systems need to be flexible due to the many different tasks they need to challenge, scalable to enable future changes in the production line, and coordinated with many different stakeholders. To build a flexibility system, a modular approach should be pursued which implements building blocks that can be rearranged and extended without too much interference with other systems. This enables the easy integration of new systems and data points, such as new sensors, into an existing architecture without the need to change large parts of the existing code. In addition, low-code platforms like Node-RED reduce the time and technical knowledge needed to perform certain tasks, such as connecting new data points. With the goal of building a scalable and performant system, multiple databases (DB) should be used and optimized for the data they store, e.g., InfluxDB for raw time series, SQL-based DB for structured data, and FTP servers for image data. While this means the datasets needed are stored in various places, it allows each data base to perform at its optimum. Building the servers, edge PCs and other hardware with overdesigned specifications makes it possible to cope with the increasing demands of recent technologies such as AI models without having to make time-consuming and costly upgrades to existing hardware.

One the IT architecture has been set up, the next step is to integrate all the shop floor assets such as production machines and sensors to ensure the availability of production data throughout the ramp-up and to enable access to the machines. The foundation for an efficient integration with minimal workload is the use of standardized data models and interfaces where possible. One of these domain standards is “OPC UA Companion Specifications”, describing important parameters and their properties throughout battery cell production. It can be used in conjunction with intelligent asset onboarding tools that can semi-automatically integrate new assets into the IT landscape, which eases the workload during this critical phase. To achieve the greatest benefit, the aim should be to implement these standardized data models in the various layers of the IT architecture, from machine connectivity, data storage, and pre-processing through to the final analysis of the data, as shown in Figure 17. However, as there is no such companion specification for battery cell manufacturing, Fraunhofer FFB and PEM of RWTH Aachen University, together with partners, are currently defining one [10]. This will reduce the time needed to connect machines and unlock the above-mentioned benefits with standardized interfaces and descriptions for all data points.

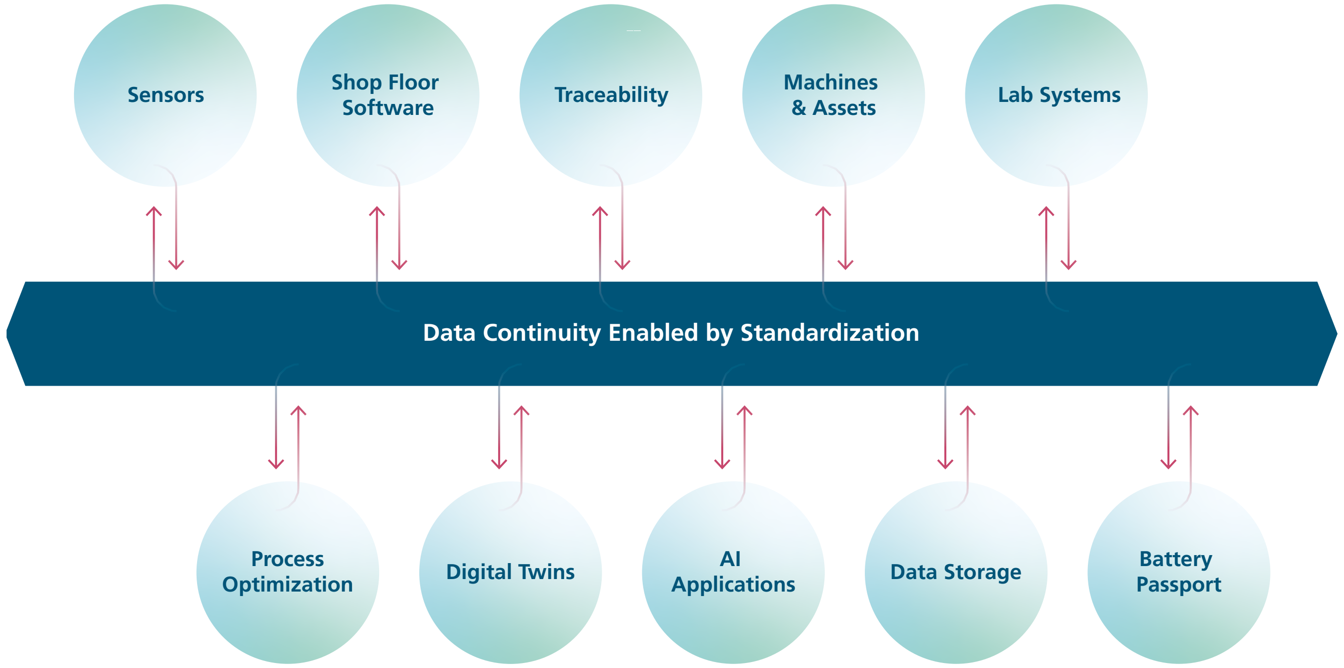


Figure 17 Example of different systems accessing data automatically using a standardized interface.

With the machinery integrated and the data available in a standardized way, they can be used to unlock benefits and optimize production. One way are black-box optimization methods such as the Bayesian Optimization which can effectively and quickly result in a good parameter set by obtaining few experiments. This method can be used with little data, and the model gets better with each experiment as more data points are added. One further advantage is that they can be used for exploration and exploitation. "Exploration" means to plan the next experiments with the goal to generate the largest amount of new information by estimating the uncertainty in the model. "Exploitation", on the other hand, means to plan the next experiments with parameters that have the highest probability of generating good results. Since we formalize expert knowledge in a structured knowledge graph, as mentioned in Chapter 6.1, we can leverage it in conjunction with data-based models. This integration allows us to enhance the accuracy and effectiveness of our analysis and optimization processes, facilitating a more comprehensive understanding of production dynamics. This expert knowledge eliminates unnecessary connections, thus reduces the complexity of the problem, and initializes the model with known influences. For example, this approach can be used with Bayesian Networks which can quantify, disprove, or find new CERs [11].

Furthermore, as battery manufacturing is a complex process with large data structures, it can benefit from various data mining and data analysis techniques, for it is important to validate expert-based CERs and to quantify the effects of a parameter change along the entire networked process chain, e.g. how a change in the mixing of the slurry will affect the properties of the cell [12]. On the other hand, clustering techniques can be used to identify and connect similar production runs and cells with similar quality markers [13]. To do this, the quality of a cell and the intermediate products must be assessed. As this can be very complex due to multifaceted quality measurements, AI methods are very promising. To enable this, a traceability system connects the product to all the process data and quality measurements generated along the production process. Lastly, automated data analysis and unsupervised monitoring techniques such as anomaly detection can be used to alert the process experts and data analysts to new and unexpected situations. This allows them to quickly react to these situations and prioritize the analysis of data and results, potentially reducing the time between the production run and the moment when the information gained is used to plan new parameter settings.

7 Our Added Value

After the challenges and possible solutions have been presented, how can ramp-up in battery cell production be mastered efficiently? Fraunhofer FFB and PEM of RWTH Aachen University offer a unique combination of knowledge, experts, and infrastructure in the field of lithium-ion batteries to shorten ramp-up times and reduce costs. As explained, practical experience with industrial production processes plays a crucial role.

The Four Pillars of Successful Ramp-up

For us, mastering the ramp-up of battery cell production is based on four pillars, as shown in Figure 18): accumulated industry experience by accompanying gigafactory ramp-ups in China, Korea, Hungary, and Sweden (1), suitable knowledge databases (2), in-house development of digitalization solutions (3), and our proprietary production infrastructure (4).

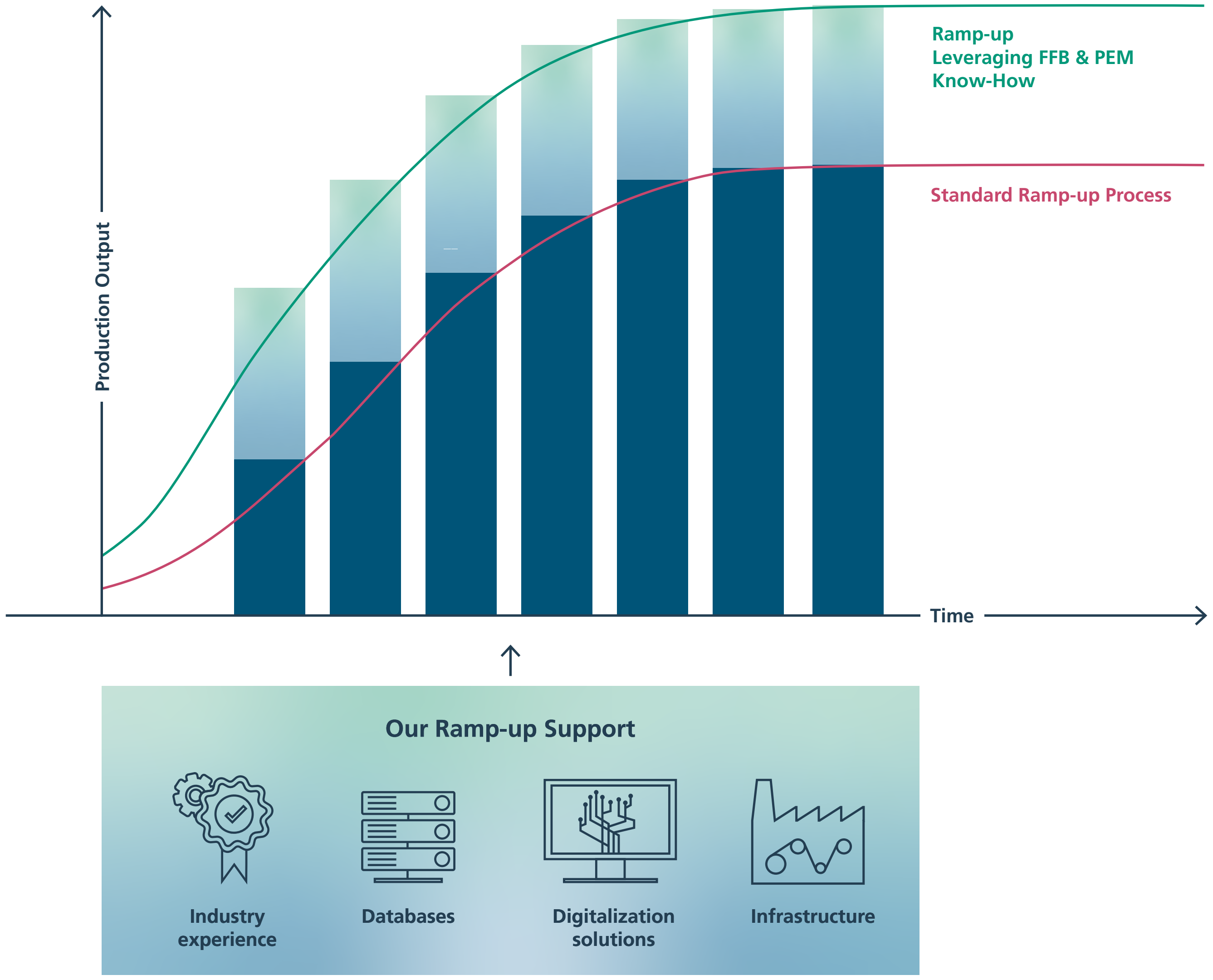
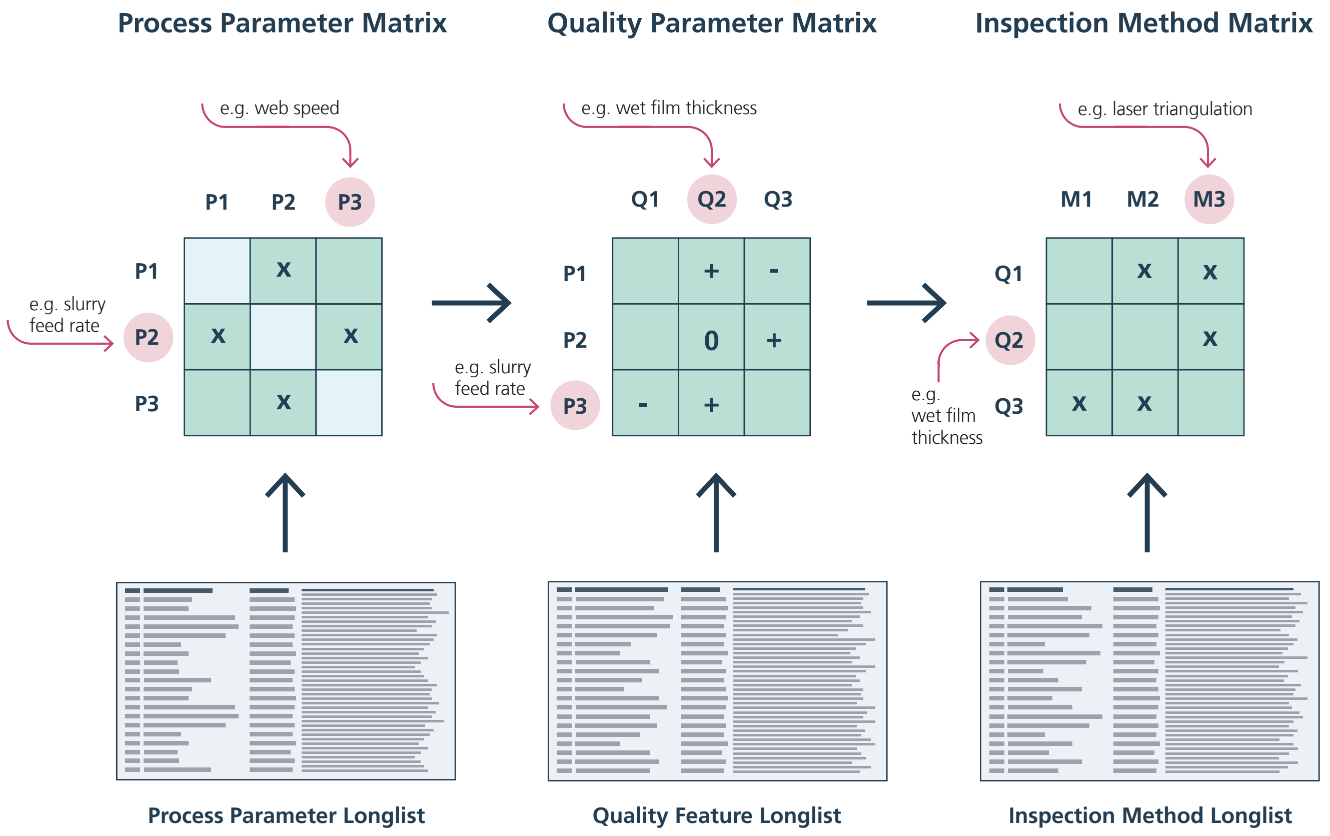


Figure 18 Unique selling points of Fraunhofer FFB and PEM

Fraunhofer FFB and PEM employ consulting teams that specialize in ramping up battery production (1st pillar). Through numerous projects in both planning and ramp-up of battery cell factories at every scaling level all over the world, these teams have gained valuable experience. This enables us to estimate which steps will take how long and what costs will be incurred. In addition, our experience gives us the opportunity to recognize typical mistakes at an early stage and help to avoid them. This enables realistic time planning and overcoming financial challenges. By accompanying gigafactory ramp-ups around the world, knowledge was gathered about which errors occur why during ramp-up and how they can be avoided. A well-known and powerful tool for determining the causes of errors still is the "Process FMEA" method. The core of the methodology is to determine possible error patterns and their causes using an Ishikawa diagram, for example. However, this requires an in-depth understanding of the processes as well as empirical knowledge from existing productions, which we can provide.

Our unique knowledge of battery production is preserved not only in the consulting teams but also in the institute's proprietary databases (2nd pillar). This includes databases of production technologies, cause-and-effect relationships, cost and energy consumption, optimal manufacturing parameters, equipment manufacturers, market data, and many more. These databases form the basis for various problem solutions during ramp-up. For example, our database of machine manufacturers contains not only the suppliers but also the corresponding technology and its advantages as well as disadvantages. This enables us to provide recommendations for alternative technologies, including the associated suppliers, in the event of problems in production. Our databases of process and quality parameters (see Figure 19) also contain knowledge about the relationship between the two. This helps to identify root causes for problems, for instance by conducting an FMEA and completing an Ishikawa diagram. Our database of inspection equipment can also be used to identify associated missing measuring equipment. All these databases are very valuable because they have grown through a large number of projects in battery production industry and enable the identification of defects, their causes, and the derivation of improvement measures.



	P1	P2	P3
P1		x	
P2	x		x
P3		x	

	Q1	Q2	Q3
P1		+	-
P2		0	+
P3	-	+	

	M1	M2	M3
Q1		x	x
Q2			x
Q3	x	x	

Figure 19 Databases covering process parameters, quality parameters, and inspection methods.

Digitalization (3rd pillar) seems to have been neglected in battery cell production. But the complexity of battery cell production requires data-based problem solving in addition to purely knowledge-based solutions. The unique combination of production and digitalization experts in our institutions enables us to develop customer-specific digitalization solutions. This supports faster factory construction and a fast and safe detection of defects in production, thus enabling higher quality and less scrap rates.

The last cornerstone is our in-house infrastructure (4th pillar). Thanks to our own infrastructure, we also know which problems occur during planning and commissioning. We have an own pilot factory which can produce 200 megawatt-hours per year, and we are currently constructing a proprietary battery gigafactory, capable of producing seven gigawatt-hours annually. Here, we can evaluate the ramp-up and its specific challenges every day including the implementation of new materials, new cell designs, new technologies, etc. Thanks to this infrastructure, PEM and Fraunhofer FFB have in-depth knowledge of how to run processes efficiently and how to react to quality deviations. This knowledge can also be transferred to large-scale production. The different scaling levels of FFB and PEM production lines represent a unique selling point. In future, all stages from laboratory and pilot to gigafactory are mapped. This enables fast and cost-efficient production runs on a small scale and subsequent upscaling with dedicated implementation of production runs in pilot-scale and large-scale production. We can share this knowledge as part of staff training courses at our facility. This also includes training in cleanrooms and drying rooms, the number of which is limited in Europe. This enables us to conduct employee training in the relevant production environment and to answer questions about occupational safety in the relevant atmosphere.

The unique combination of these resources and capabilities allows us to effectively address organizational, technical, and digital challenges, resulting in superior financial performance.

This makes us the ideal partner. Together with us, you will be mastering the battery production ramp-up!

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