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Framework for the Application of Industry 4.0 in Lithium-Ion Battery Cell Production

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Abstract

The application of Industry 4.0 in lithium-ion battery cell production enables companies to achieve increased product quality and global competitiveness, since the majority of value creation takes place in this process. Studies have shown, that improving production performance is the most effective way for battery cell manufacturers to become competitive in the increasingly globalized market. To achieve operational excellence, battery manufacturers must adopt the concepts of networked and digitized production. However, holistically introducing digitalization, data systems and Industry 4.0 methods in all sectors of lithium-ion battery cell production currently poses a major challenge as comprehensive approaches are not available. Therefore, a tailored methodology for the evaluation of suitability and introduction of digitalization and Industry 4.0 is presented. The approach addresses all production-related sectors from logistics to plant engineering to quality management via so called application areas. Multiple development stages divide these into the maturity levels in terms of Industry 4.0. To design each application area and stage, Industry 4.0 use cases from battery cell producers, plant manufacturers, and battery-related research projects are clustered and abstracted for general accessibility. It is shown, that abstracted application areas may be assigned either to all production sectors such as communication or to specific fields such as quality methods. Based on the application areas, corresponding toolboxes are established forming the core of a digitalization guide. To increase the level of maturity with regard to Industry 4.0, the presented paper aims at enabling companies to apply appropriate tools from the toolbox to their production. The systematic and efficient development and implementation of digitalization as well as the holistic assessment of a company's maturity are enabled and provide an essential tool towards increased competitiveness.

Keywords

Lithium-ion Battery Cell Production; Competitiveness; Digitalization; Industry 4.0; Production Planning

1. Introduction and state of the art

Developing energy storage systems to meet the growing global demand for storage capabilities sustainably providing electrical energy is one of the key challenges of our time. The development of a variety of storage technologies is driven forward, among which the lithium-ion battery cell plays a key role. Its wide range of advantageous properties has resulted in its application in a wide range of products, among which the electric vehicle is the most prominent representative. Despite the rapid development of the lithium-ion battery, it is still facing technological challenges ranging from the improvement of key characteristics such as energy density and safety, elaborating possibilities for recycling and especially establishing cost-effective mass production [1]. The latter in particular plays an important role concerning market penetration. To overcome this challenge, the holistic digitalization of factories and implementation of Industry 4.0 methods can assist [2]. In various industries, a significant increase in competitiveness through improvements such as reduced downtime, increase in throughput, and lower energy consumption have already been shown. In addition, companies are enabled to collect process and product data along the entire value chain and evaluate it using intelligent algorithms enabling product and process development [3,4].

The European lithium-ion battery production capacity is expected to increase to a 16.8 % share of global production capacity in the next decade [5]. Battery cell producers are relying on the introduction of digitalization and Industry 4.0 methods to sustainably increase their productivity and compete in the highly contested market. In Germany, Varta AG, and Daimler AG are increasing their efficiency and flexibility [6,7], Switzerland-based iQ Power Licensing is aiming at shorter throughput time and lower energy consumption, Northvolt is holistically implementing Industry 4.0 approaches in Sweden [8], Freyr Battery introduced digitals twins of all processes in Norway [9], Tesla, Inc. uses holistic digitalization paired with automation in the USA [10], and Contemporary Amperex Technology Co. Limited is doing the same in China [11]. However, since the implementation is a complex interdisciplinary problem, companies face several challenges ranging from the selection of suitable sensors, their networking to the establishment of automated communication and autonomous process control [12,13]. In addition, the maturity determination regarding Industry 4.0 cannot be performed and a clear vision does not exist. Therefore, the efficient introduction of digitalization and Industry 4.0 requires a systematic, holistic and intuitive approach [2].

Since the topic of digitalization and Industry 4.0 in battery cell production is still new to the field of research, only a few approaches identifying and addressing the arising challenges exist. Data acquisition and evaluation, as well as cyber-physical systems in cell production, were analysed [14,15,16], and a holistic, data-driven approach to battery cell manufacturing was demonstrated [17]. In addition, data mining methods were applied to battery cell manufacturing [18] and digitalization conceptually addressed regarding traceability, digital twins, and end-of-life prediction [19]. It can thus be concluded that there is currently no guide for supporting companies in the holistic introduction of digitalization and Industry 4.0 in battery cell production. Consequently, the potential of the next level of industrialization cannot be accessed efficiently and intuitively to competitively manufacture lithium-ion battery cells.

Thereby, all production-related aspects such as process technology of the individual manufacturing processes, the associated machine and plant technology, and quality management to ensure the required quality must be addressed. Furthermore, organizational aspects of production planning, control and logistics must also be included for a holistic view of Industry 4.0 in battery cell production. Although there are extensive studies and guidelines on battery cell production [20,21] and digitalization [22,23], there is no known combination of the two with a holistic view of all aspects of production technology. Digitalization and Industry 4.0 in battery cell production have been named as a necessary technology breakthrough ("Red Brick Wall") [20]. Therefore, the development of the framework and corresponding toolboxes for the digitalization of battery cell production is the goal of this paper and is intended to make a fundamental and sustainable contribution to competitive battery cell production in Germany. So-called toolkits represent one component of the digitalization guide. New functions in the sense of Industry 4.0 and the Maturity Index according to SCHUH ET AL. are to be derived from the toolkits for Industry 4.0 and successfully implemented [24,25]. How this can be achieved is explained in this contribution.

2. Methodology for the development of toolboxes for digitization

This chapter refers to the development of the toolboxes, which form the fundamental basis of the digitalization guide. The framework of the toolboxes is presented at the beginning and their characteristics are explained. The toolboxes are linked to the existing Industry 4.0 Maturity Index according to SCHUH ET AL. [25]. This index, postulated by SCHUH ET AL., describes different degrees of digitalization with the help of levels that build on one another and is already established in the industry. Finally, the procedure for developing the toolboxes is shown and explained.

2.1 Framework of toolboxes

In order to enable industrial companies to access Industry 4.0 in a transparent and comprehensive way, the entire production is divided into the following production areas: production planning and control and logistics, machine and plant engineering, quality management, and process technology (Fig. 1). Due to the fact that certain areas within battery cell production cannot be assigned to any specific area alone, an overarching area is added. For example, part of the overarching area relates to data. Since all production areas have to access it, no clear allocation can happen. The specific production areas in combination with the overarching area are the basis for the toolboxes. Each area is assigned its own toolboxes. All toolboxes provide content and methods that define development stages. These development stages represent different levels or stages of digitalization and Industry 4.0 and are based on the development stages from the Industry 4.0 Maturity Index according to SCHUH ET AL. [25]. The main terminologies used in this paper are summarized in figure 1.

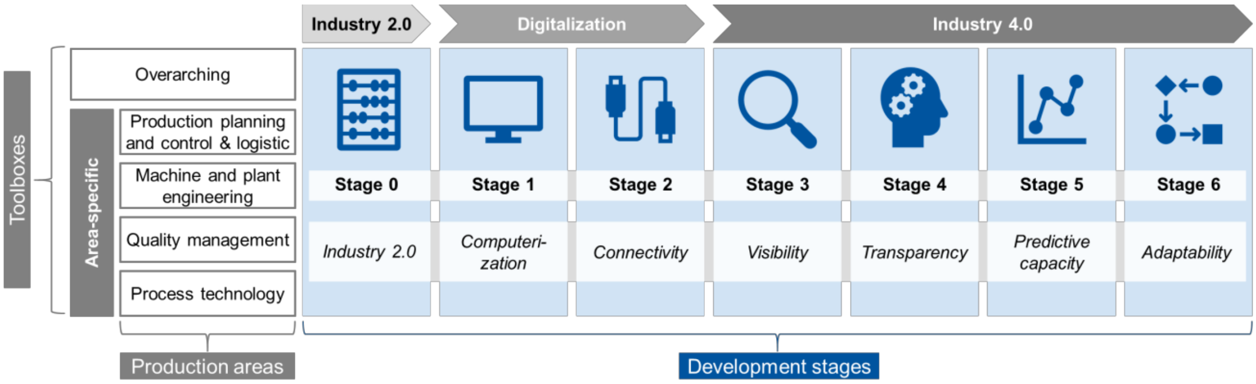

Figure 1: Overview of the framework toolboxes

The six stages represent the forms of digitalization and Industry 4.0 from computerization to adaptability. For the purpose of completeness, another stage 0 is added to represent the case of no digitalization. Stages 1 and 2 can be taken from the existing Maturity Index. Since the Maturity Index generally aims at the entire corporate structure, the definitions of levels 3 to 6 must be adapted to production. To achieve stage 3 sensors must be integrated into a process in order to capture product and process data. For example, in a calender, distance sensors could be integrated to continuously determine the existing layer thickness after the calendering process. In subsequent stage 4, the process-product-effect relationship is determined. At this stage, an interpretation is made of the influence of an input parameter on the output parameter. With the help of this understanding, a digital twin of the equipment or process can also be built and linked to the sensor data. In relation to the calendering process e.g. a correlation between roll gap and layer thickness could be determined. At the same time, the digital twin of the calendering process is built up and could visualize the effects of gap adjustment on layer thickness.

At the next higher level 5, the digital twin is used to predict the output parameters on the basis of the available input parameters. There is no direct link to the machine. In the case of calendering, the required roll gap can thus be predicted for a desired layer thickness, but only for a given material. The roll gap must then be set manually on the machine. The final stage adaptability is achieved when the system can not only predict the output, but also simultaneously adjust the system parameters accordingly. In the calendering process described above, manual adjustment of the roll gap is no longer necessary, since the system carries out the adjustment autonomously.

The framework of the toolboxes enables the user to classify his production quickly, comprehensively and clearly differentiated with regard to digitalization. Different areas can be targeted, as certain users or companies have different focal points. For example, a cell manufacturer might focus on the digitalization of its logistics, whereas a machine manufacturer of a calender might focus on process monitoring. Besides the stage analysis, a target stage to be achieved can also be defined, visualized and continuously tracked. In addition, the necessary steps to achieve the target stage can be taken from the toolbox. The toolboxes thus provide the decisive tool for a guided and comprehensive implementation of Industry 4.0 in battery cell production.

2.2 Toolbox development

The fundamental approach for developing each toolbox is shown in Fig. 2.

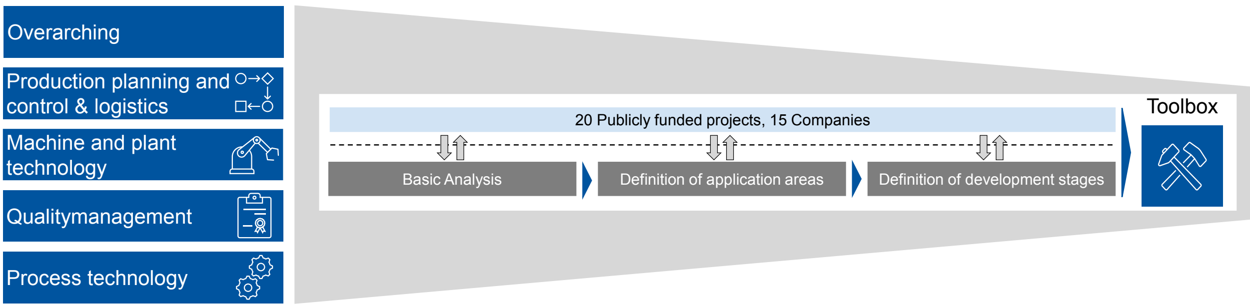

Figure 2: Procedure for the development of the toolboxes

The starting point for developing the toolboxes is a comprehensive basic analysis of the addressed production areas. To determine the status quo in battery cell production, the first step was to analyze pouch cell production by determining and summarizing all necessary input and output data along with established process and digitalization technologies. In addition, a project screening of 20 publicly-funded projects concerning battery cell production was carried out. Due to the currently running "Dachkonzept Forschungsfabrik Batterie" (meaning umbrella concept battery research factory) and various battery cluster initiatives of the Federal Ministry of Education and Research (BMBF) in Germany, there is intensive cooperation between all battery institutes operating in Germany. Based on the cooperation in the cluster "Intelligent Cell Production", there is close contact to parallel projects, which are regularly screened and surveyed within the framework of this project.

With the help of this project screening, the projects were classified according to the contents of the four production areas and their degree of digitalization. Furthermore, specific use cases of digitalization in battery cell production were developed from the individual projects. Alongside this screening, interviews were conducted with 15 industrial companies that currently support the BMBF Cluster Initiatives with a focus on battery cell production. The companies were e.g. cell manufacturers, equipment manufacturers, or specialists for sensor technology in the battery field. The interviews were conducted over a period of six months using a standardized questionnaire (multiple choice and open-ended questions) so that the results of all interviews could be compared.

With the help of the interviews, it was thus possible to identify the current status quo of the implementation of Industry 4.0 and challenges in dealing with Industry 4.0. The main purpose of the interviews was to collect the various advances made by different players (material manufacturers, equipment manufacturers, cell manufacturers etc.) and to identify deficits. Based on the process analysis, the interviews, and the project screening, it is apparent that the specific production areas, but also the overarching area, need to be divided into different categories called "application areas". The application areas were determined based on a large number of interviews and the contents discussed. An attempt was made to aggregate and cluster the different topics. The application areas are not to be considered singular, as there are also interfaces between the different areas. For reasons of complexity, the interfaces are omitted at this point, so that they are not considered further for the time being.

The application areas are unique and customized according to the corresponding topic. Additionally, they describe applications within this area. Due to the application references, these are referred to as application stages in the following. In addition to the application area, the application stages form an area-specific basis for the integration of suitable Industry 4.0 methods. To build up the content of the development stages the identified use cases of digitalization in battery cell production are abstracted and used to assign specific Industry 4.0 content and methods. The resulting toolboxes of the different areas can be viewed in the further course as one large toolbox that provides all important information, content and methods.

3. Results and discussion

With the presented framework and procedure for the creation of the so-called toolboxes, 12 application areas were identified in total (see fig. 3). Multiple Industry 4.0 use cases from battery cell producers, plant manufacturers, and battery-related research projects were analyzed, clustered, and abstracted for general accessibility. The analysis concludes, that the toolboxes for the application areas can be divided into different sections. The first, general section can be applied to all production or company sectors.

For example, the application area "Data" can be assigned to the overarching toolbox since it accrues irrespective of the company's department. Data generation and analysis can occur at both the planning level and shop floor level. Other than the overarching application area, the following additional application areas can be identified: 1) Logistics, production planning and control, 2) Machine and plant engineering, 3) Quality and 4) Process management (see fig. 3). For each of these, toolboxes with defined characteristics based on the maturity index development stages are developed. These toolboxes, with their characteristics and methods, form the core element of a digitalization guide in battery cell production.

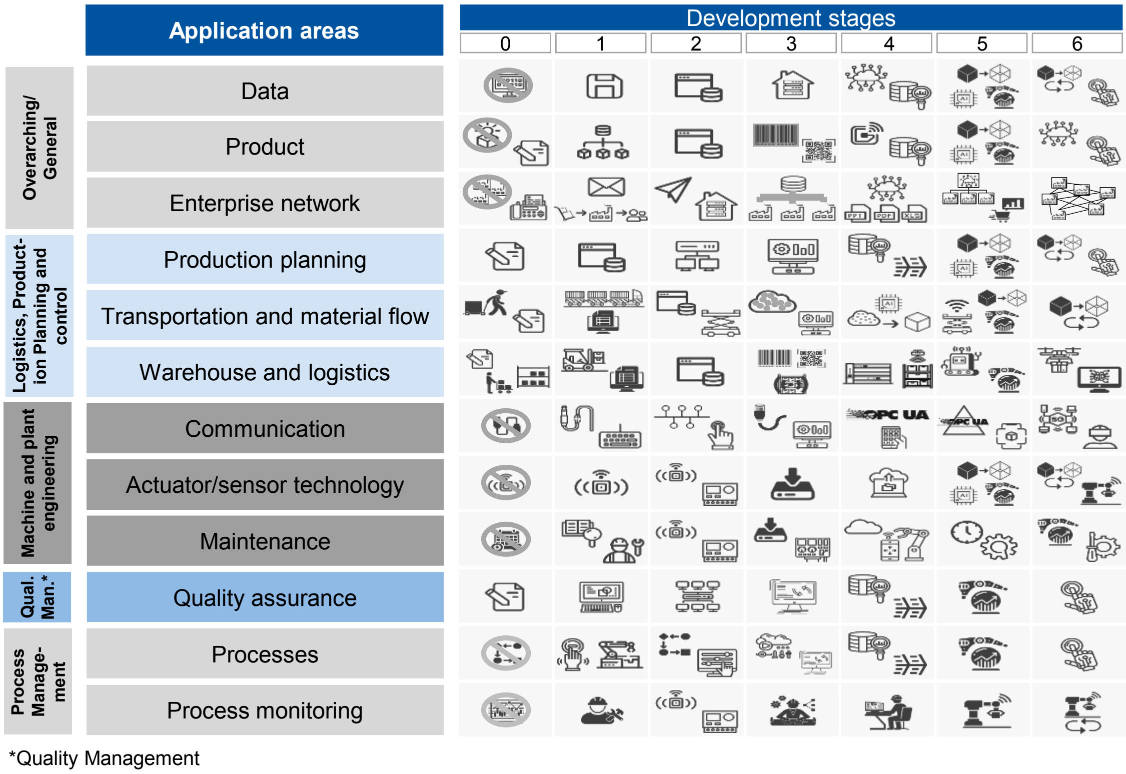

Figure 3: Application areas for digitalization in battery cell production

To identify or increase the level of maturity in regards to Industry 4.0, an analysis of the different toolboxes has to be conducted. Each application toolbox consists of relevant methods and tools to implement Industry 4.0 from a scale from zero to six in regards to the maturity index. To establish or increase the maturity level in the enterprise networks different approaches can be considered.

The application area "Enterprise Network" (see fig. 4) is presented in detail as an example toolbox and the process methodology to be used is shown. An enterprise network defines a company wide network as a form of coordinated cooperation and collaboration between several departments and locations. This toolbox focuses on approaches in the context of enterprise-wide networking. The starting point for the considerations is the question of how networking and collaboration can be optimized and costs reduced with the help of Industry 4.0. Improving the networking and communication of companies opens up synergies and avoids duplication of work. Networking production with other areas of the company, e.g. communication between the lithium-ion battery production facility and separator or anode material production facility results in unified IT solutions, standardized workflows, and consistent file formats that benefit the entire company. When improving the enterprise network up to the highest development stage six, whereas all data from the different production sites is continuously exchanged, an autonomous order distribution and plant adjustment in the global production in real time can be expected. To achieve this stage (six) of Industry 4.0, all previous stages from zero to five have to be achieved and implemented successfully in order to obtain this new development stage within the enterprise network.

The toolbox "Enterprise Network" provides detailed specifications of the development stages and therefore encourages company specific solution finding: the next development stages towards Industry 4.0 are always considered by the user(s) in the context of their company specific use case. This means, that the ideal or right target stage for the different production areas, can be an individual decision made by a company. This can result in different "ideal" target stages, depending on the current company orientation, but in the long term a high development level should be aimed for to ensure increased efficiency and quality in lithium-ion battery production.

In addition to the “Enterprise Network”, the other toolboxes enable companies to apply appropriate tools from the toolbox to their production in order to increase their level of maturity with regard to Industry 4.0. The other eleven toolboxes are structured and developed according to the same system and provide information on how to digitalize the warehouse, production processes, quality management, or how to implement predictive maintenance in production. The systematic and efficient development and implementation of digitalization, as well as the holistic assessment of a company's maturity with the toolboxes are enabled and provide an essential tool towards increased competitiveness. With the toolboxes, a more efficient Industry 4.0 development process can be achieved due to the strategic framework and the laid-out use case examples and best practices generated over the course of the interviews mentioned earlier. The existing application areas and development stages can be used and adapted according to the company's own needs, so that process development does not start from zero. The subsequent implementation of Industry 4.0 methods or applications in the company is also facilitated with the toolkits, as the contents of the toolkits build on each other and complement each other. The methodical overview can be a relief and increase in efficiency for an inexperienced user.

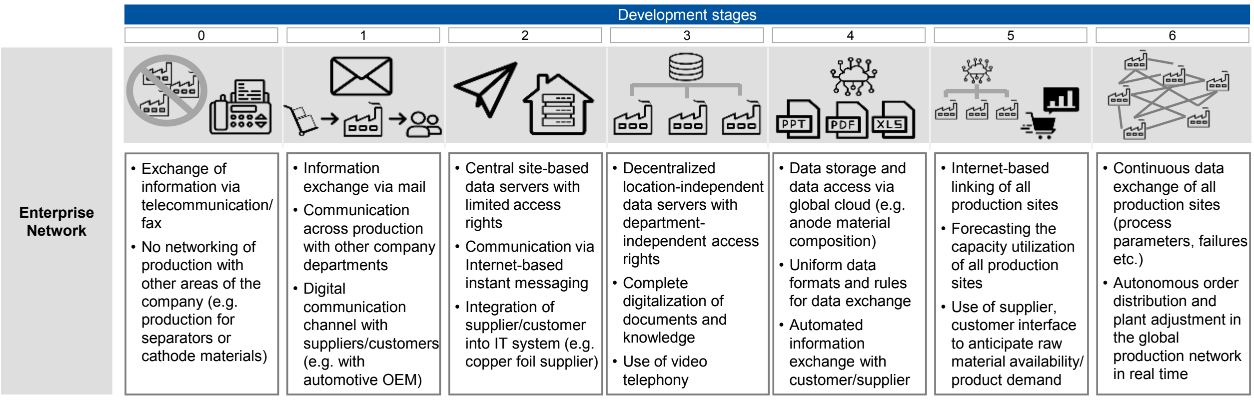

Figure 4: Digitalization application and toolbox for industry 4.0 methods within an enterprise network

4. Conclusion and outlook

This paper presents a framework consisting of toolboxes for different application areas and stages for measuring and improving the maturity of Industry 4.0 in lithium-ion battery cell production. For this purpose, so-called toolboxes are used to determine the different stages of Industry 4.0 in different areas of battery cell production. Furthermore, actions that are needed to implement or increase Industry 4.0 in the different areas can be derived from the toolboxes. The main limitation and question remaining is concerning the right target stage for the different production areas, and how companies can define their target stages. These questions have to be analyzed and answered according to the companys’ specific strategy and mission. In summary, the toolboxes and the framework provide an overview and descriptions of tools or stages, but no guidance on how (e.g., how to implement or how to define a target state).

In the further course of the project, the methodology will be tested with the partners from lithium-ion battery industry and research. A workshop concept will be used for this purpose. To demonstrate the applicability of the methodology, the workshops will be validated in a broad field of industrial sectors in the area of battery cell production. In order for the toolboxes to be used, the terms Industry 4.0 and digitalization are defined at the beginning of each workshop. This is followed by an as-is analysis of the workshop participant using the toolboxes. Based on this, company-specific target states or wishes are defined, which signifies a higher development stage in the different application areas. When defining the target state, however, the cost-benefit ratio needs be considered and analysed by the individual company in question in order to ensure feasibility. The necessary analysis tools and methods will be developed in the next project phase as part of the overall methodology. Following the cost-benefit ratio, individual recommendations and/or projects are then derived from the target specification using creative methods. The defined measures or projects are prioritized and then implemented in the company. The aim of the validation workshops is to iteratively adapt the methodology to enable optimal measurability and further development of Industry 4.0 in battery cell production. The results will be summarised in a detailed guideline, which is intended to provide industrial companies with a transparent and holistic approach to Industry 4.0 in the field of battery cell production.

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