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Interaction of Digital Twins in a Sustainable Battery Cell Production

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Abstract

In this paper, we propose a procedure for identifying suitable fields of action for digital twins, selecting meaningful use-cases to realize the benefits of digital twins, and prototyping their implementation in the context of battery cell production. For this purpose, we present a framework that maps out the various fields of action for realizing the benefits of digital twins in the sustainable factory of the future. In addition, the identification of suitable use-cases in the respective fields of action is described. Using the example of prototypical implementations from battery cell production, it is illustrated how different digital twins interact with each other towards the vision of sustainable production. This focuses on the digital machine, building, and product twin. The aggregation of the twins and their use enables a conservation of resources and an increase in efficiency in the production of the cells and enables the optimization of subsequent value chain steps.

Keywords: Digital twin; Battery; Battery cell; Battery cell production; Sustainability

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1. Introduction

As climate change progresses, a shift from the use of conventional energy sources to renewable ones is necessary, which is accompanied by the indispensability of efficient storage of electrical energy [1]. This is resulting in a boom in demand for battery cells – according to experts, the market for lithium-ion battery cells will grow from around 200 GWh annually today to over 2,000 GWh by 2030 [2]. However, the production of battery cells goes hand in hand with enormous complexity for companies. Ensuring sustainability in the production of the cells is proving to be a key challenge, with potential for improvement becoming apparent in various areas of production:

- The traceability of battery cells to enable product-specific analytics and to be able to improve recycling or remanufacturing processes;
- an increase in the efficiency of machines for producing the cells;
- the optimization of production facilities in terms of resource efficiency.

The digitalization and networking of production associated with the fourth industrial revolution holds great potential with regard to increasing sustainability [3]. The acquisition and useful processing of data, which is already being generated in large volumes in the production environment, is essential in this context. The aggregation of different types of data is an elementary criterion for this [4]. The use of digital twins can provide a solution here. However, the concept of the digital twin is still in its infancy – a clear definition, goals of a digital twin, and its components have not yet been established in the field of battery cell production.

2. Battery Cell Production

In recent years, lithium-ion technology has emerged as the best solution for a large number of applications that rely on mobile energy storage [5]. With regard to the battery cell type,

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the question of the dominant design has not yet been resolved. In principle, a distinction is made between cylindrical cells, pouch cells and prismatic cells [5]. The production process of the cells can be divided into electrode production, cell assembly and the formation and activation of the cells (see Fig. 1) [6].

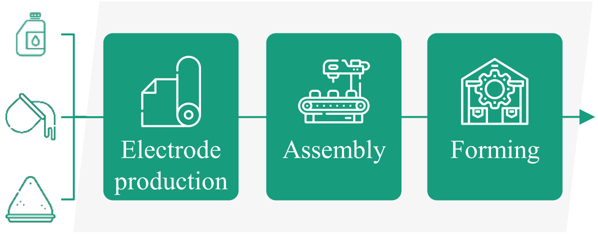

Fig. 1. Processes of battery cell production [6]

Electrode production is the critical factor in cell production - which is why many processes have to be carried out under cleanroom conditions and, accordingly, digitization of the building can also be useful in optimizing the product. The cathode and anode determine the core properties of a cell - such as capacitance and impedance - and are therefore essential for its quality [6]. The production of anode and cathode follows the same process steps. The electrode foils are each coated with a prepared paste of active materials, dried, calendered, cut into the required format and finally dried again under vacuum [7,8].

The assembly differs depending on the cell type. In principle, however, for all cell types the electrodes are inserted into a housing, the cells are sealed and filled with electrolyte [7]. The final stage of cell production is formation. After assembly, the cells are initially in an uncharged state. Some characteristic features of the cell are formed only with the initial charging of the cell, which takes place during formation. Finally, the functionalities of the cells are tested [6].

3. Idea of the Digital Twin

The concept of using a twin, i.e., replicating a product to reflect the behaviour of the original, was already used by NASA for the Apollo missions. At that time, an exact replica - the "twin" - of the spacecraft remained on Earth in order to use it to draw conclusions about the condition of the original by simulating conditions in orbit [9]. Since the term "digital twin" was first mentioned in a NASA publication in 2010, the idea of the digital twin has been increasingly discussed in science and industry [9,10]. In this context, core elements describing a digital twin are: the physical world, the virtual world, the flow of data from the physical to the virtual world, the flow of information in reverse order, and virtual subspaces [11]. This idea of the digital twin is visualized in a simplified way in Fig. 2.

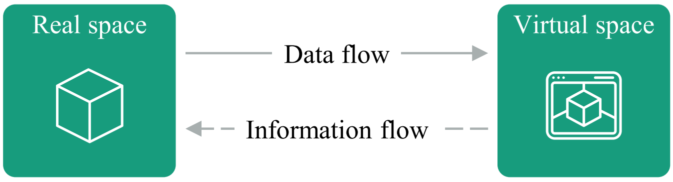

Fig. 2. Conceptual ideal for product lifecycle management [11]

However, the limited dissemination as well as the variety of possible applications of digital twins have led to the fact that so far no complete and universally valid definition of the digital twin exists [12]. This diversity also results in the absence of a unified approach for generating a digital twin [13]. The conceptualization and realization of the digital twin in complex production environments will be illuminated in the following in the context of battery cell production.

4. Digital Twins in a Sustainable Battery Cell Production

To achieve the common understanding and definition of digital twins in the battery cell production, we analyzed a wide range of existing definitions from different domains [10,11,14–17]. Furthermore, multiple workshops with more than 25 experts and researchers were conducted. In those workshops the different requirements users have regarding the digital twin were identified. This led to features and dimensions that the digital twin must support. As a result the mutual understanding is that a digital twin is a digital representation of a specific object. The digital twin encompasses the properties, states, and behavior of the object via data, models, and information [16]. The underlying database includes all data from the entire lifecycle that can be useful in each lifecycle phase.

As depicted in Fig. 3, the scope of the digital twin spans from a *digital building twin*, to a *digital machine or asset twin* down to a *digital product* (i.e. battery cell) *twin*. Digital twins for buildings describe the building information model and aggregate contents from environmental effects and dependencies like the energy consumption, logistics simulations and building automation components for monitoring and control. Digital twins for the machines, allow the aggregation of machine process data and adaption of the processes based on the machines properties and capabilities at runtime. Also, the digital twin for a machine can incorporate the aggregated data and information for predictive maintenance use-cases. Lastly, the digital twin of the product describes the product throughout different steps and links different production data to the final product and its properties. By that, the twin for the product can provide product quality indicators and metrics based on the whole production. Those twins can interact with each other allowing them to represent complex productions. Processes in contrast to buildings, products and machines do not have a physical representation and therefore do not have a digital twin. Instead, the interaction between those other digital twins over time describes a process precisely. This also makes it possible to optimize production in

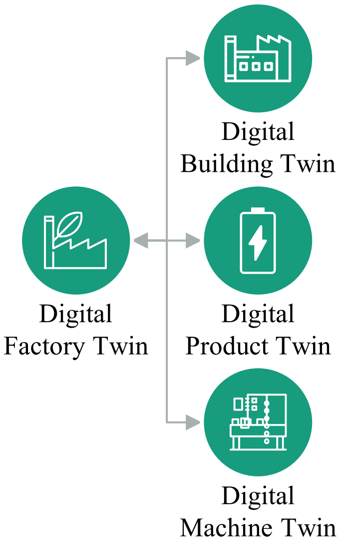

Fig. 3. The digital twin for the factory is made up from multiple digital twins for different areas.

terms of sustainability, for example by using resources in a forward-looking and minimizing way, using energy in a time-optimized way, or simplifying downstream value creation steps.

5. Realization of Digital Twins in Battery Cell Production

As stated in the previous sections, different areas for the digital twins exist. To identify use-cases that provide additional value in the production line with respect to achieving set sustainability goals, the different domain experts and production staff are needed as they should be supported by the digital twins. For this, we use direct and indirect methods. Direct methods include interviews with the experts and production staff to collect their insights, challenges and ideas what would be helpful to them and production. This method focuses on the knowledge and personal point of view of the persons. Supplementary to the direct method, we choose to use indirect methods as well. Such methods include observations of the persons during the production and work-descriptive interviews to gain insight of the actual working steps and flows. By that, indirect methods allow the identification of potentials without the potential bias of the persons. Finally, those insights and information are aggregated and comparable challenges and links between are identified.

Using the results from the identification methodology described, we deduce a variety of use-cases for the three areas of the digital twin described before. In this section we briefly present one use-case per digital twin area which is being implemented iteratively. Those use-cases per area also focus on different aspects of added value for digital twins.

5.1. Digital machine twin

For the first digital twin area, we identified a use-case for machines in the production. For this use-case, we present the information and data in a dashboard as a one human interaction point with them shown in Fig. 4. In the electrode production step, the mixing of the active materials to be used for coating of electrode foils is a complex process step critically impacting the final electrode quality. In our case, we use a screw extruder to mix and knead different raw materials resulting in the paste to be dispensed on the electrode foil. During the extrusion process, data is acquired from the machine and aggregated in a time-series database. In addition, a 3D model of the machine is available, which can be rendered or used pre-rendered in here. Those information and data are representing the current state, which can be read from the PLC HMI of the machine itself or by standing in front of the machine respectively. By using additional information about the setup and machine process, key performance indicators for the machine performance and machine process stability can be calculated. Such a calculated indicator is the kneading concentration, which allows to determine how the concentration of the different raw materials fed into the machine in the kneading step is and develops. In consequence, we have a set of different data sources and data processing steps the users in the production are interested in.

In the dashboard shown, the weight of different feeders (top middle), the drive speed (top left), and the drive speed (mid left) are visualized. For the calculated metrics the kneading concentration is presented for the different feeder materials (top right). The plate at the end of the machine is described by its temperature (bottom right). The actual feeder throughputs are shown in different ways. First, the actual rates enabling the users to check on the relation to each other in the in the 3D model (middle) while at the same time to double check having a visualization of the overall throughput shown in the bottom left of the dashboard.

5.2. Digital product twin

For the digital twin area of the product, a quality prediction during the production process can add significant value to all people involved in the production. The concept including the use-case application is shown in Fig. 5.

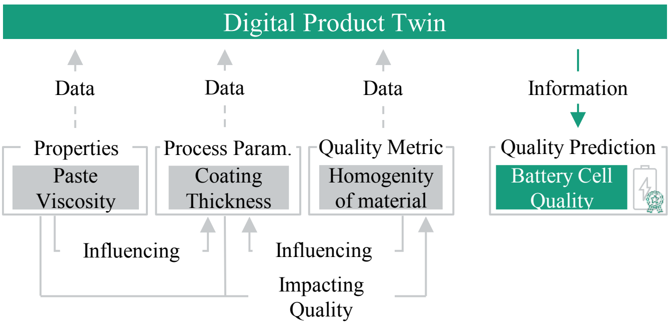

Fig. 5. Using the data from material, process and metrology in combination with information regarding quality impacts allows a battery cell quality prediction. The digital twin serves as the data interaction point.

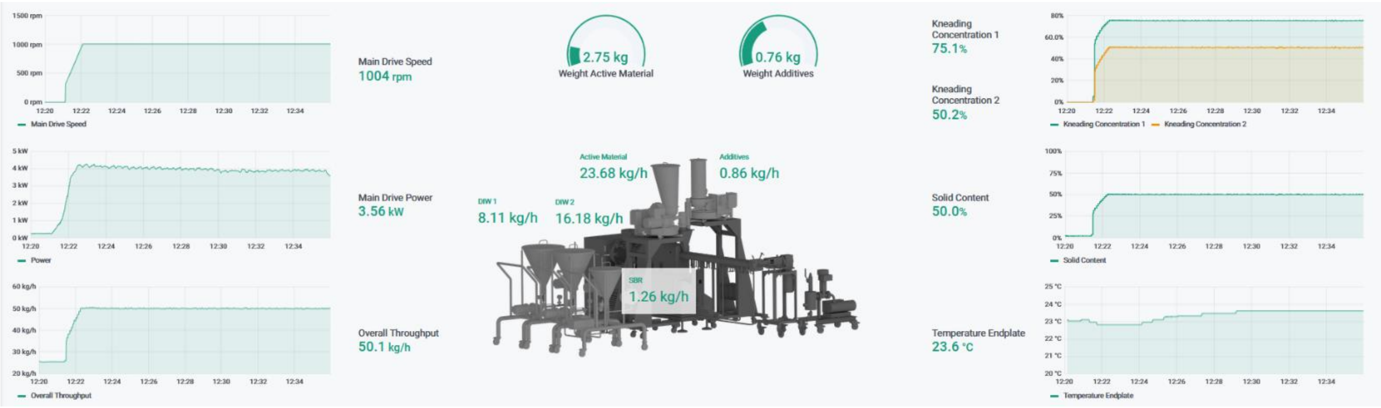

Fig. 4. A dashboard for the extrusion experts allowing them to gain insight to the process parameters of the digital machine twin.

Currently, there is no standardized and overall finalized list of all parameters and quality metrices of the process steps with quantified impact information. Still, for some parameters and metrices the impacts are known and there is active research ongoing in this area. By that, the integration of known and upcoming insights is of interest and describes an interesting use-case for the digital twin of the battery cell during production. As there is a variety of relevant information and data in the production line with potential of impacting the battery cell quality, this use-case requires a large amount of data sources and systems to be connected.

In this case (Fig. 5), the properties of the active material paste like the viscosity influences the process parameter like the coating thickness in the coating process step with regards to the aimed quality metric. By that, the property itself impacts parameters and the quality directly and indirectly. The data regarding those is collected and made accessible through the common data access point, the digital twin for the product. Using this aggregation of data sets in combination with expert knowledge for parameter influences of battery quality, the live data from the whole production is used via the digital twin to generate a live prediction on the resulting battery cell quality. This prediction itself can be shown to the users directly, but as well is fed back to the digital twin itself, allowing other components and systems to use the results. This feedback into the digital twin also feeds into the traceability of the battery cell. By aggregating the data from different sources, process steps and linking to other digital twins, the whole production process for this product can be traced and inspected on a data basis.

5.3. Digital building twin

Regarding the area of the building, logistics are essential for a high-scale production line with interdependencies and multiple sub-processes. The modeling of the logistics along the production line in the building can be done in different ways and the digital twin is the place where they come together and different users can get the level of detail based on their requirements. In this case, we use two modeling approaches. In the first approach we use a traditional material flow simulation in Plant Simulation which allows distinct and detailed simulation of the logistics in the building and detect potential space bottlenecks during production. Further, we create an abstraction layer for the simulation, as process experts mostly only change a smaller set of parameters actively, while other parameters are taken from other systems (e.g., currently available amount of resources). This abstraction layer adds the information from other sources directly, while the user only adds a subset of the available parameters for the simulation. This allows the process expert fast interaction with the simulation without the full complexity. In addition to this, we create a 3D model along the building with respect to the machine models. This model allows the production staff to explore the production and their logistic workflows interactively and identify problems intuitively. These different models for the logistics are linked to each other via the digital twin while for the users the digital twin is the representation that suits their requirements best as shown in Fig. 6.

In this section we have shown three different use-cases for the digital twin in the battery cell production. Those use-cases add value for the users inside the full production line by aggregating different data and information while providing interaction interfaces for users and systems based on their requirements.

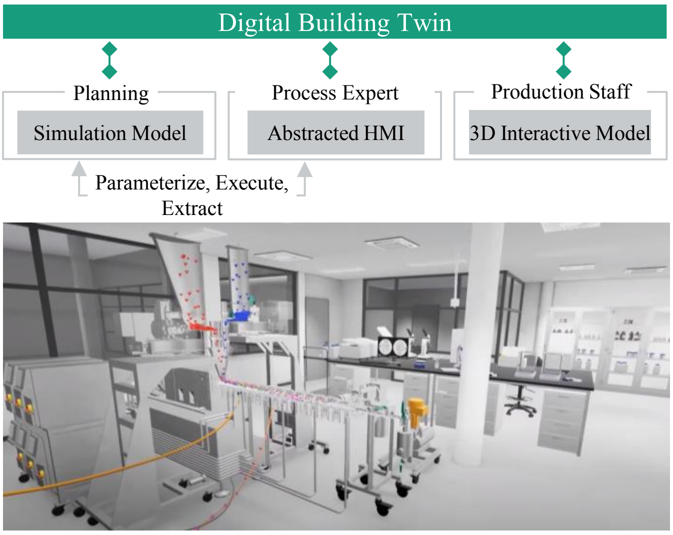

Fig. 6. Visualization of the functionalities of the digital building twin in battery cell production

6. Conclusion & Outlook

Currently, we see a lack of a standardized definition for the digital twin in battery cell production. As such a definition is needed to achieve best possible integration and information exchange, we set up such a definition with a variety of expert partners. In consequence, the definition provides a view on the digital twin in terms of the interaction between different twins in specific application areas. By using this definition we are able to implement different use-cases inside the battery cell production adding value and support for the experts and staff inside the production.

This definition also builds a base for further research questions in the future. Inside the battery cell production, we look into production machines as our machines and focus on the linked machine twin. In contrast, for a machine vendor, the machine is the product with a product twin in their production. This transfer from product to machine twin introduces some challenges for the model that need to be investigated.

We identified three different application areas for the digital twins (building, machine, product), where everything impacting the production should be clustered into. With the emerging of new concepts like mini-environments, where a large machine builds the small room-in-room for other machines, the boundaries of those definitions are challenged. Also, further investigation within multiple domains may find further clusters that have to be integrated as separate digital twin application area.

While this common definition works for the battery cell production, other production lines exist without such a common definition, e.g., the fuel cell production line. In future work those other production lines have to be investigated whether these concepts and definitions can be transferred to them analogously.

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