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The digital twin in battery cell production

Potential for efficient and sustainable production

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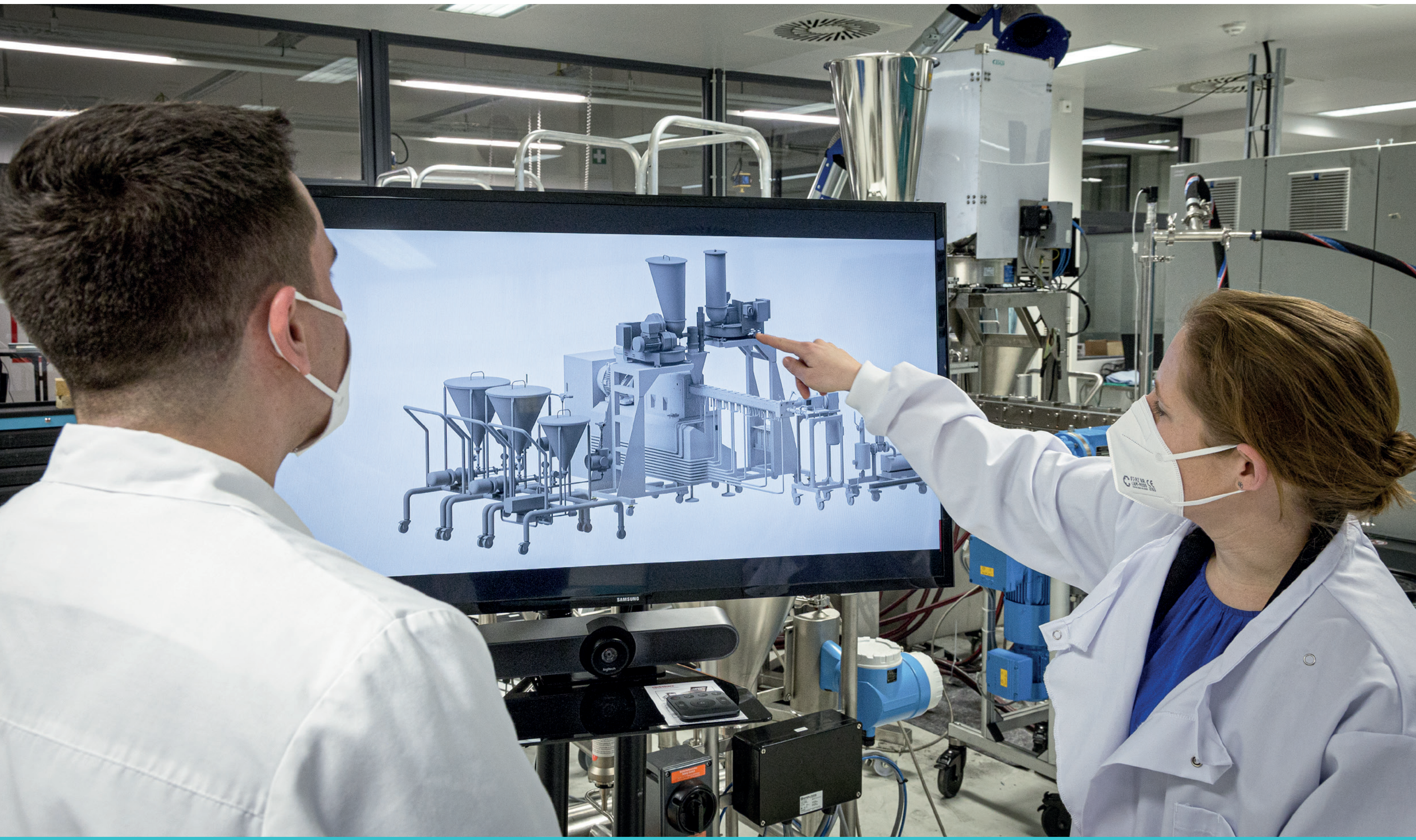
Content



The concept of the digital twin as the representation of a physical object is currently under development and is delivering promising first results. At the same time, the goals and the definition of digital twins differ, sometimes significantly, depending on the area of application and use case. Therefore, the descriptions and concepts of digital twins in a specific application cannot simply be transferred to new fields of application.

Meanwhile, battery cell manufacturing is a key of the energy and mobility transition that is still characterized by high costs as well as scrap rates and will benefit enormously from the use of digital twins. To provide a basis for the development of digital twins in battery cell manufacturing, this white paper presents a unified definition for the digital twin in battery cell manufacturing, based on existing work. For this purpose, three forms of the digital twin are described: the building twin, the machine twin, and the product twin. Each of these forms must be examined in detail so that components of the respective forms can be identified, exemplary use cases can be shown, and concrete goals as well as challenges can be defined. Based on the concepts described in this white paper, the digital twin will be used in battery cell production to track, optimize, and control products and processes in the future. In perspective, this can significantly improve energy, raw material, and cost efficiency.

The use of digital twins offers diverse potentials in battery cell production

Current estimates predict that global demand for lithium-ion battery cells will increase from 200 gigawatt hours per year to 1.5 up to 3 terawatt hours in 2030 [1]. One of the reasons for this is the growing demand for battery cells in the automotive industry. The shift toward electromobility is expected to account for 80 percent of total battery demand in 2030 [2]. Numerous battery cell manufacturing facilities are currently being established to meet this growing demand: Around 40 battery factories are just expected to be built in Europe by 2030, which will be able to cover about one-third of the global market demand [3, 4]. However, battery cell manufacturing is highly complex and poses several challenges, such as ensuring high cell quality while maintaining high process stability and efficiency. Against the background of advancing climate change, it is necessary to avoid greenhouse gas emissions and the use of critical materials during battery cell production as much as possible [5-7].

Within this framework, the European Commission has presented a proposal for a regulation to promote the circular economy and sustainability as part of the Green Deal. Among other things, this contains the mandatory "Battery Passport" for all batteries with a capacity of more than 2 kilowatt hours placed on the market in the EU from 2026 [8]. As with other initiatives, for example the Supply Chain Sourcing Obligations Act [9], the aim is to improve supply chain transparency.

One approach to achieve this goal is to use digital twins as closely linked, virtual copies of physical objects. For example, digital twins enable process optimization during production and product traceability from data obtained during the manufacturing process [10]. In addition to process optimization, digital twins also enable data-driven optimization to reduce the ecological footprint and resource consumption.

It is important that the positive effects from the use of digital twins, such as more efficient and sustainable production, outweigh its ecological costs and do not worsen the overall life cycle assessment of battery cell production in the sense of a so-called rebound effect [11].

Digital twins open a wide range of potentials — for example, to trace the properties of battery cells during the production process, to optimize the efficiency of production facilities or with regard toregarding the use of resources. However, the concept of the digital twin is still in its infancy: A clear definition, goals of a digital twin and its components are not yet available in battery cell production. Central tasks are the identification of suitable use cases that offer added business value and the design and technical implementation of the digital twin.

This white paper describes how the digital twin of a battery cell production can be designed. It provides an overview of the status quo of the digital twin in production and explains the concept for a digital twin in battery cell production. This results in various forms of the digital twin, whose components, challenges, and structures are presented here. Using application examples, the white paper shows the added value of digital twins, illustrates the interaction of the different forms and classifies the digital twin in battery cell production.

Definitions and applications of digital twins in production

Already in the 1970s, NASA was working with the idea of a physical twin of a spacecraft remaining on Earth, so that problems and their solutions could be recreated and tested [12]. These real twins were gradually augmented and replaced with digital images and simulations to draw conclusions related to the real behavior of the original. The term “digital twin” was first used by NASA in 2010 [13]. Since then, the concept has been discussed and further developed in industry and research. Nevertheless, no general concept about the structure and content of a digital twin has been established yet. For this reason the concept is also still missing for battery cell production.

Various theoretical definitions of the digital twin

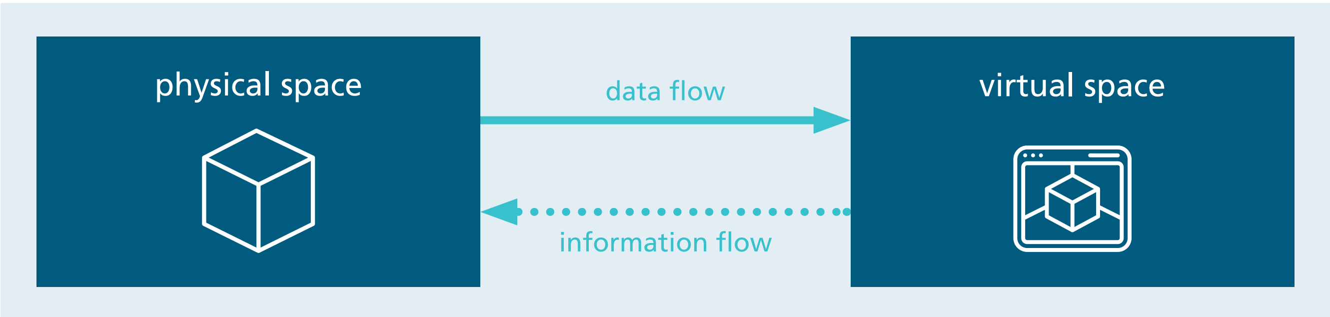
The digital twin is a representation of an object from the real world in the digital world. An object can be physical, such as a machine or a building, or virtual, such as a plan or a process.

In recent years, many definitions of the digital twin have appeared in the global community (see Table 1). The authors focus on partly different aspects such as the use of physical simulations [13] as opposed to purely data-driven aggregations [14]. In further definitions data-driven aggregations are explicitly named as well as models. Furthermore, the respective authors describe the purpose of the digital twin as an aggregation of information sources describing the properties and behavior of the physical entity [15-17]. The definitions by Boschert and Rosen [18] and Bergs et al. [19] encompass the entire lifecycle of the mapped entity and the associated aggregations of information.

A coordinated and standardized definition is currently being developed at the international level by ISO/IEC JTC 1, the joint technical committee of the International Organization for Standardization and the International Electrotechnical Commission, in the corresponding working group of SC 41 WG 6 for the Internet of Things and the digital twin [20].

The Internet of Things and the digital twin are often considered together. Although both concepts build on the three central design principles of Industry 4.0 (networking, information transparency and decentralized decision-making [24]), they address different application areas independently of each other. While the Internet of Things refers to the

Figure 1: Conceptual ideal for product life cycle management adapted from Grieves and Vickers [25]



networking and communication of assets via the Internet and the description of their basic capabilities in this context, the digital twin is dedicated to information transparency and the collection, management, modeling, and organization of data [24].

On the conceptual level, the digital twin establishes a direct link between the real world and the virtual image by mirroring the objects into the virtual world in such a way (see Figure 1) that the user can access and operate them accordingly. Interoperability, communication, and integration are realized through the mapping rules, which must conform to the standardized principles of information and data modeling. This is the only way to ensure a seamless flow of data and information between the two spaces. For this reason, the implementation of the digital twin is supported by numerous standardization activities, especially in an international context.

Digital twin as an international standard

The first internationally coordinated, normative description of the most important concepts, the use cases and the reference models for the digital twin is being developed in the ISO/IEC JTC 1 working group [20]. The standards beeing developed aim to provide a solid basis for a structured approach to the design of digital twins.

At the national level, numerous organizations and associations have joined forces under the leadership of the newly founded user organization "Industrial Digital Twin Association" (IDTA) [26] and in coordination with Plattform Industrie 4.0 [27]. The aim is to drive forward the implementation of the digital twin in accordance with the 2030 Guiding Principles for Industrie 4.0 [28] in Germany.

One of the essential conditions for mirroring an object in the information world is the unambiguous description of its properties [29]. Therefore, one of the central tasks of the digital twin is to map each object with its functions and specific properties in such a way that it can be described unambiguously. This can be done,

Table 1: Various definitions of the digital twin

Authors	Definition of the digital twin
Schafto et al. [13]	"[...] an integrated multiphysics, multiscale, probabilistic simulation of an as-built vehicle or system that uses the best available physical models, sensor updates, fleet history, etc., to mirror the life of its corresponding flying twin. The Digital Twin is ultra-realistic and may consider one or more important and interdependent vehicle systems, [...]."
Boschert and Rosen [18]	"[...] a comprehensive physical and functional description of a component, product or system, which includes more or less all information which could be useful in all — the current and subsequent — life cycle phases."
Stark et al. [15, 17]	"A Digital Twin is the digital representation of a unique asset (product, machine, service, product service system or other intangible asset), that compromises its properties, condition and behavior by means of models, information and data."
T. Kuhn [21]	"Digitale Zwillinge sind digitale Repräsentanzen von Dingen aus der realen Welt. Sie beschreiben sowohl physische Objekte als auch nicht-physische Dinge wie zum Beispiel Dienste, indem sie alle relevanten Informationen und Dienste mittels einer einheitlichen Schnittstelle zur Verfügung stellen. Für den digitalen Zwilling ist es dabei unerheblich, ob das Gegenstück in der realen Welt schon existiert oder erst existieren wird."
Boschert et al. [22]	"[...] refers to a description of a component, product, system or process by a set of well-aligned, descriptive and executable models: The Digital Twin is the semantically linked collection of the relevant digital artifacts including design and engineering data, operational data and behavioral descriptions. The Digital Twin evolves with the real system along the whole life cycle and integrates the currently available and commonly required data and knowledge."
Kunath and Winkler [14]	"[...] the Digital Twin of a physical object [is] the sum of all logically related data, i.e. engineering data and operational data, represented by a semantic data model."
Industrial Internet Consortium [16]	"A digital twin is a formal digital representation of some asset, process or system that captures attributes and behaviors of that entity suitable for communication, storage, interpretation or processing within a certain context. The digital twin information includes, but is not limited to, combinations of the following categories: ▪ physics-based model and data, ▪ analytical models and data, ▪ time-series data and historians, ▪ transactional data, ▪ master data, ▪ visual models and computations."
ISO/IEC JTC1 / SC 41 WG 6 [23]	[A digital twin is a] "digital representation of a target entity with data connections that enable convergence between the physical and digital states at an appropriate rate of synchronization. Digital twin have some or all of the capabilities of connection, integration, analysis, simulation, visualization, optimization, etc. Digital twin may provide an integrated view throughout the lifecycle of the target entity."

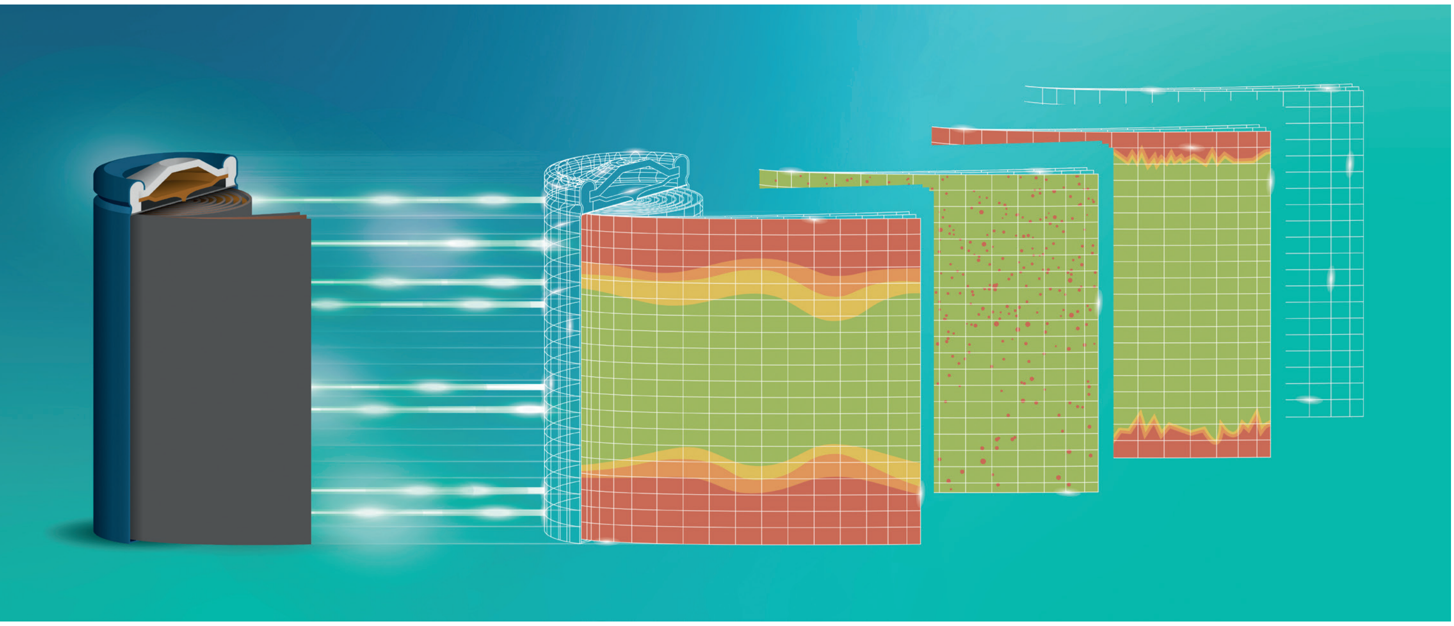


Figure 2: By linking process parameters and position data, the quality of the cell can be estimated and predicted

for example, along the levels of the Industrie 4.0 reference architecture model (RAMI 4.0) [30] and the associated lifecycle phases.

As a cross-industry, technical implementation, the standard for the Asset Administration Shell [31] is being actively developed internationally with the IEC 63278 series in the IEC/TC 65/WG 24 working group [32]. In addition to the most important basic information about the object, the administration shell contains the so-called submodels [31], which provide a defined structure and enable a standardized description of properties, parameters, variables and capabilities of an object.

Lack of practical implementation in battery cell production

In practice, no digital twin of a complete battery cell production including the factory building, the production machines and the product has been implemented and published yet. In other industries and in research, digital twins are applied to individual machines, production lines and products, which show great potential for cross-industry knowledge transfer to battery cell production. Examples include the design and implementation of a digital twin in a networked Micro Smart Factory [33], the use of digital twins for anomaly detection [34], adaptive process planning and optimization [35], or the implementation of a digital twin of the battery for optimizing the use and evaluation of degradation [36]. Good reviews of other publications on the use of digital twins are provided by Kritzinger et al. [37], Fuller et al. [38], and Liu et al. [39].

The assumption that few advanced practical implementations of digital twins are known and publicly viewable is consistent with the surveys published by Detecon [40] as part of a study: While 92 percent of the participating companies in this study stated that the digital twin will have a noticeable positive influence on future digitization projects, in 2019 only twelve percent of the companies surveyed that they were already using a digital twin, which meets the definition of the respective respondent.

Against the background of the different definitions and the lack of exemplary practical implementations of digital twins for battery cell production, it is necessary to develop a uniform understanding of them. Successful implementation can only be ensured with a uniform, generally valid understanding of the term and appropriate design of the components of the digital twin for battery cell production. How these components can be designed for battery cell production is part of the conceptual design and implementation of the digital twin in the "FoFeBat" project.

Understanding and developing a digital twin in battery cell manufacturing

In the large-scale project "FoFeBat" project (shorthand for "Forschungsfertigung Batteriezelle") funded by the German Federal Ministry of Education and Research (BMBF) and the state of North Rhine-Westphalia, the concept of a digital twin in battery cell manufacturing was developed together with eight project partners. For this purpose, the partners jointly developed the goals and components, including the infrastructural integration.

Battery cell production

For many battery cell applications, lithium-ion technology has so far proved to be the common solution [41]. The production of battery cells can be divided into electrode production, cell assembly and cell formation [42]. Electrode production forms a crucial process step of cell production. The two electrodes — cathode and anode — determine the core properties of a cell and are decisive for its quality [42]. Their respective production follows the same process steps. The electrode foils are coated with a paste of active materials, dried, calandered, cut into the required format, and finally dried again under vacuum [43, 44].

In assembly, the anode, cathode, and separator are transferred to the functional cell structure by winding, folding, or stacking and inserted into the housing including insulators. The cell is then filled with electrolyte and sealed [44]. After formation, the functionalities of the cells are tested [42].

Representation of a physical entity in digital space

In the first step on the way to the digital twin of battery cell production, precise goals and expectations must be defined. For this purpose, the goals relevant to battery cell production at Fraunhofer FFB were consolidated from the literature. The digital twin is the representation of a physical entity in the digital space and is fed with data from the physical space, among other things. According to Stark et al. [17] and the Industrial Internet Consortium [16], the digital twin includes "selected characteristics, states, and behaviors" of the physical entity. Targets can be diverse and depend on the particular use case. Therefore, the development of the digital twin in battery cell production is directly influenced by the occurring use cases.

General objectives are [17]:

- Information gathering and analysis [45],
- Information supply,
- Decision support [14],
- Control of autonomous systems [46] and
- Enabling the optimization in the physical space.

Here, emphasis is placed above all on an overarching exchange of information [21].

Added value of a digital twin

For which use case a digital twin is developed depends strongly on which physical entity it represents. General use cases are mainly found in simulation and data analysis. The use cases in data analysis can be classified into four levels: descriptive, diagnostic, predictive and prescriptive. There are many different applications here in process and product optimization, process monitoring and prediction.

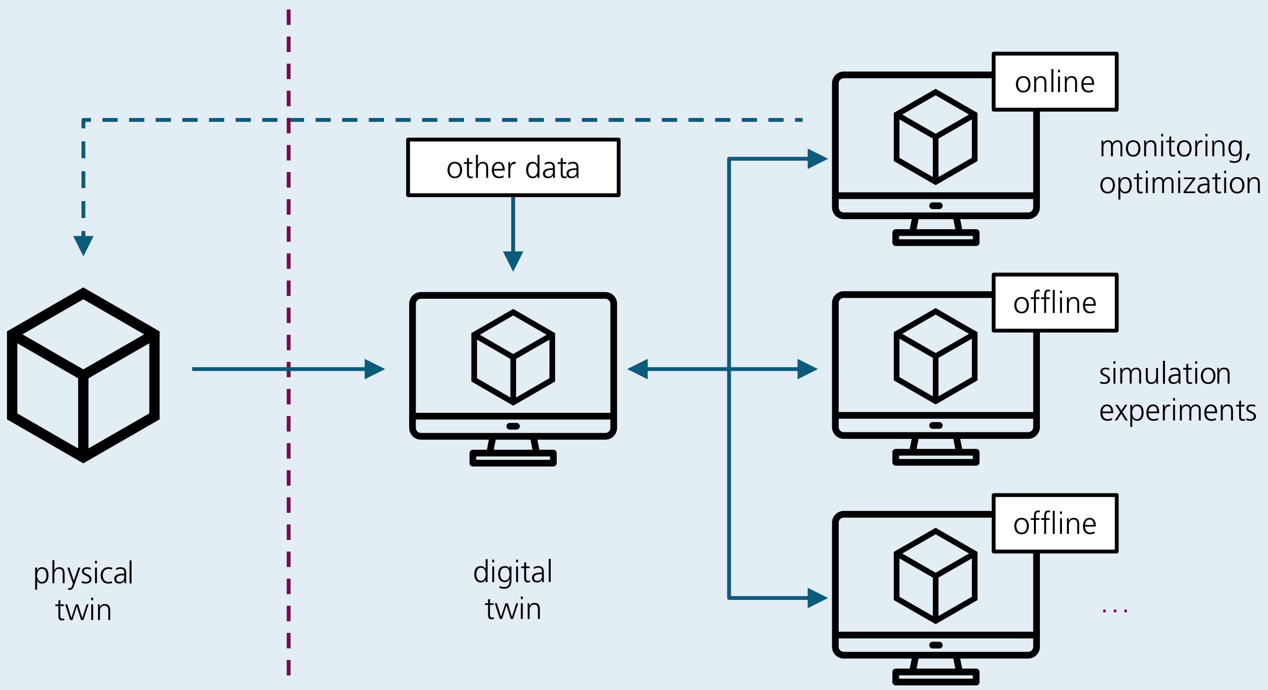
Concrete examples that involve direct or indirect added value are predictive maintenance of machines, product quality prediction, traceability of products through the process, virtual commissioning of machines, and predictive environment control of buildings [47]. Digital representations can also be created for immaterial objects such as processes, material flows, or services. A process is represented as an aggregation of digital twins and their changes over time.

Digital twin as an enabler for simulations

The literature shows different concepts of how digital twins and simulations can be intertwined. It can be deduced that simulations are a possible, although not a necessary, component of digital twins in battery cell production. Depending on the use case, it may be useful to integrate simulations. Simulations can be used to make manufacturing more efficient. For example, time and costs can be saved during virtual commissioning before the machine is start up, or ramp-up times can be shortened after changes in the process. Running virtual experiments can reduce material costs and equipment can be used optimally.

There can be different instances of a digital twin that can answer different questions depending on the use case and can operate on different levels [16]. Figure 3 shows different instances of a digital twin, which are divided into online and offline instances. Online instances have a direct link to the physical twin, the represented physical object, and can transmit commands and information through it.

Figure 3: Instances of a digital twin (adapted from [16])



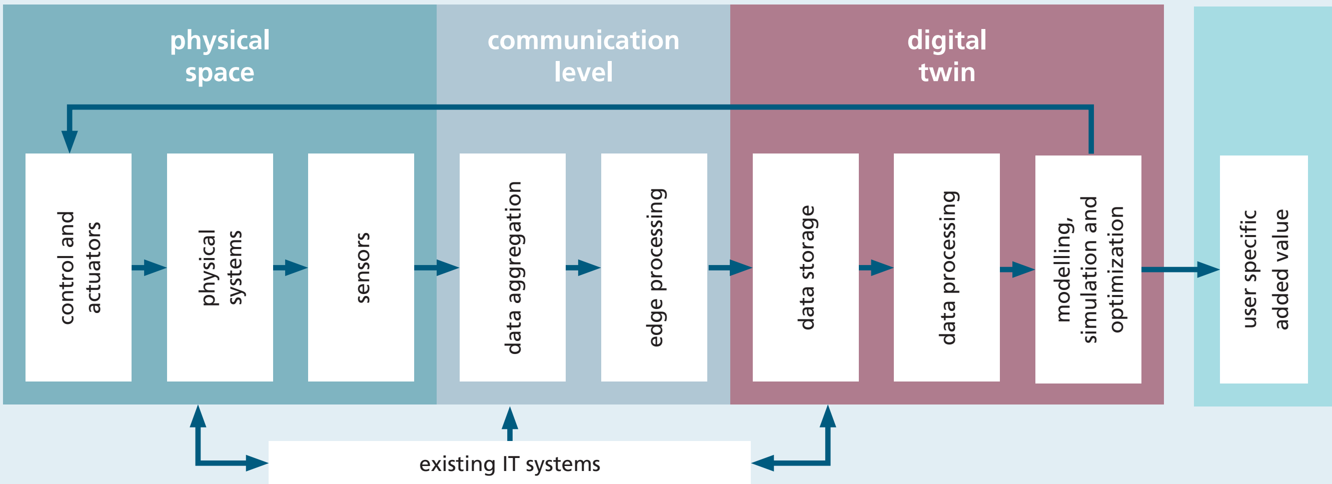


Figure 4: Framework of a digital twin with links to other IT systems (adapted from [48])

Offline instances can simulate behavior based on current values without directly influencing the physical counterpart.

Digital twins can enable simulations and evaluations. Models and simulations can be transferred back to the digital twin along the life cycle of a product. Simulations can run both inside and outside the twin [17].

Within the digital twin, there is a direct exchange of information between simulation and other instances via suitable interfaces. But simulations stored outside the digital twin can also serve as sources of information for digital twins and in turn use data from the digital twin. Here, access between the simulation model and the digital twin should enable bidirectional data exchange.

This can be done in the form of a feedback loop, which, depending on the use case, takes place in an overarching and automated manner. Various interfaces are required for this to be able to connect the applications to the digital twin. In addition, this data is required for individual, non-automated evaluations or at specific points in time.

This requires flexible and manual access to analysis or simulation results. On the one hand, such an approach enables the use of data and results from other analyses and simulations from the digital twin as input parameters. On the other hand, simulation results based on current input parameters gain relevance for the further process of battery cell production. In addition, the applications associated with the digital twin benefit from the simulation results in a way that they can be used, evaluated, and further analyzed by other digital twins. Thus, a more comprehensive data and information basis exists for better behavioral analyses and forecasts.

The digital twin bundles the data of the battery cell along its life cycle and enables analyses as well as predictions.

Data aggregation in one access point

A central question is which technical functionalities the digital twin comprises and how it interacts with and is embedded in existing structures. A digital twin aggregates data in one access point and makes it available for different purposes. It can also make information available via standardized interfaces. At the same time, the digital twin is not intended to replace existing IT systems, but rather accesses them.

It is a membrane that aggregates and provides the required information based on the underlying systems and databases.

The existing IT systems accessed by the digital twin cover, for example, data acquisition (production data, supplier data, building data, etc.), production-related functionalities (ISA95[1]; order processing, production control, maintenance, etc.), interfaces (IIoT, ERP, MES, etc.[2]) and other tasks depending on the area under consideration (APS, CRM, BIM, ...[3]).

Framework of a digital twin

A digital twin is, as shown in Figure 4, the digital representation of a physical object. A communication level connects the physical object to its digital counterpart. Data, information and models can flow unidirectionally or bidirectionally via this interface, enabling both simulations in the digital layer and control of the physical layer.

Interfaces to existing IT systems, services and other digital twins complement the information derived directly from the physical twin. Finally, the digital twin enables application-dependent and use-dependent gain of added value. These can be individual use cases made possible by the digital twin, such as visualizations.

Building on the definitions presented for digital twins, the following definition emerges for the digital twin in battery cell manufacturing:

"The digital twin is a digital representation of a specific object. The digital twin comprises the

- features,
- states and
- behaviour

of the object over

- data,
- models and
- information." [15]

It includes all data, models and simulations from the entire life cycle that can be useful in each of the life cycle phases.

1 International Society of Automation

2 Industrial Internet of Things (IIoT); Enterprise Resource Planning (ERP); Manufacturing Execution System (MES)

3 Advanced Planning Scheduling (APS); Customer Relationship Management (CRM); Building Information Model (BIM)

Forms of the digital twin for battery cell production

Machine twin, product twin and building twin

Digital twins can be developed in the context of battery cell manufacturing for the production machine, for the battery cell itself, and for the building. These forms offer high utility, are representative of battery cell manufacturing, and can be considered physically separate.

Depending on the application, they play different roles in battery cell production (see Figure 5):

Digital machine twin: This comprises all production-relevant machines in the factory.

Digital product twin: This incorporates information, quality data and other characteristics on raw materials and all intermediate and end products, including the parameters of various processing operations.

Digital building twin: This contains all the components and information necessary for the construction and operation of the factory building.

The digital twins of the machine, product, or building are merged in the digital twin of battery cell manufacturing.

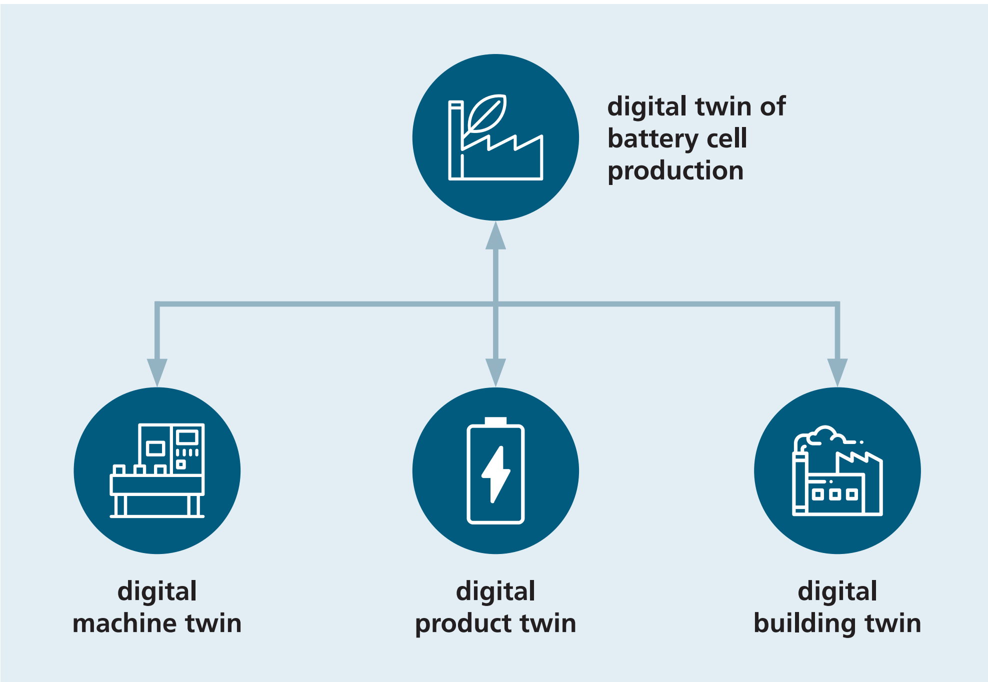


Figure 5: The digital twin of battery cell production and the three defined forms of digital twins

The digital machine twin

Connecting production machines and cross-process optimization

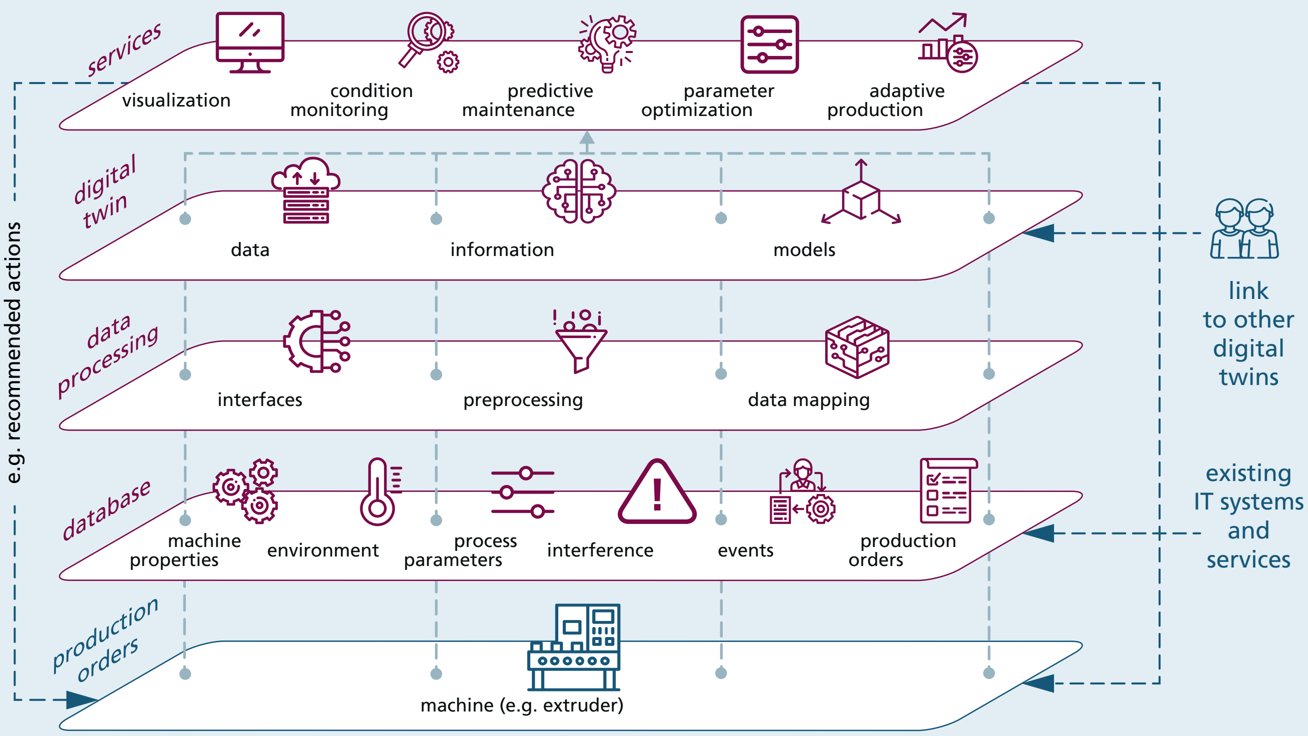
The focus of this form of the digital twin is on the production machines for battery cell manufacturing. Digital machine twins should enable the monitoring of machine states and process data. Data analyses can be used to improve machine maintenance, reduce wear and tear, and shorten maintenance times. The machine twin also offers the possibility of faster decision-making through aggregation and visualization of the relevant data, for example for production employees, machine managers or for production planning. The aim is to increase the efficiency of the machines and the respective process to achieve economical and sustainable production.

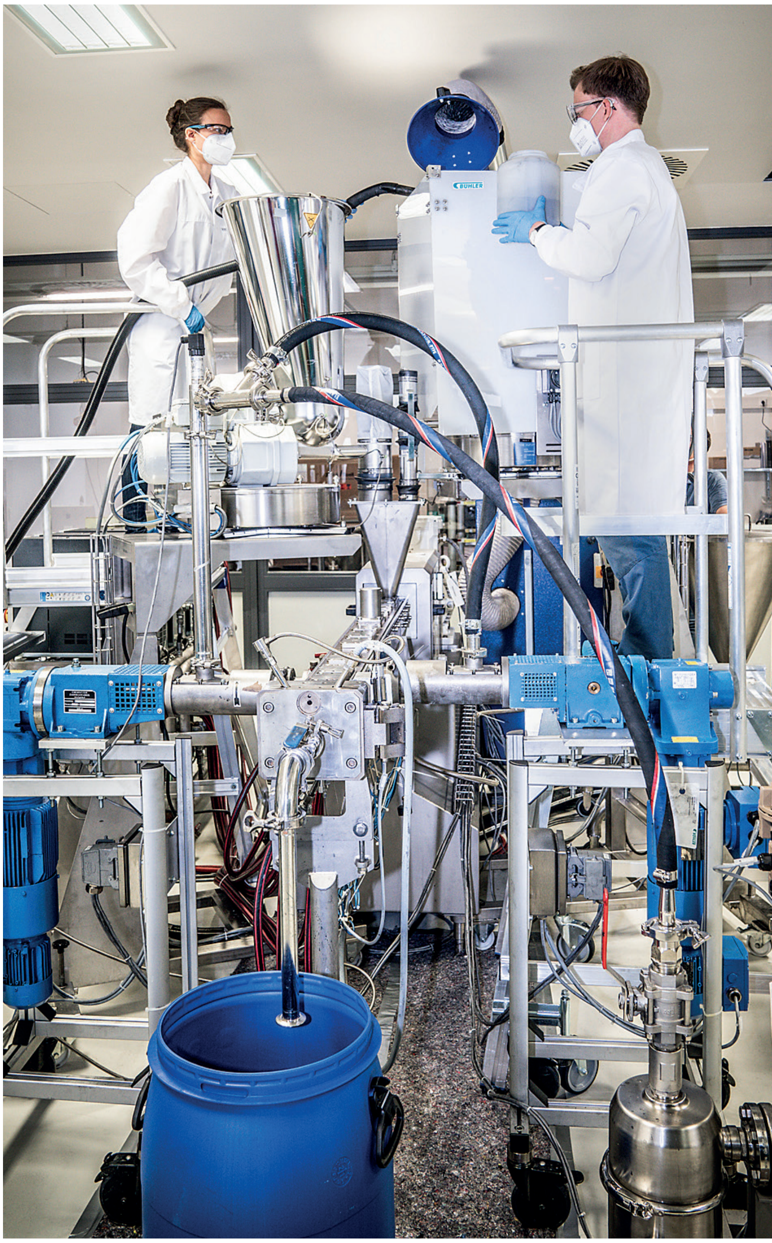
The individual machine twins also form a basis for digitally linking the entire process chain. Their holistic consideration and optimization offer enormous potential in battery cell production due to the many process steps from electrode production and assembly to the formation of the finished cell.

Data basis from real application

If successfully designed and implemented, the machine twin provides a realistic representation of the machine. Therefore, a data basis as comprehensive as possible must be created, which contains, among other things, process data, information on machine states as well as event data. The quality of the event data, which contains, for example, information and times of maintenance and special machine states, depends on input from maintenance staff and machine operators. These inputs are — in addition to the process and condition data of the machine as well as the information of the machine manufacturer

Figure 6: Structure of the digital machine twin





resulting from remote maintenance — the basis of subsequent predictive models of the machine (cf. [49]). To represent the condition of the machine as realistically as possible, it is necessary to sensitize process participants to record event data realistically. If the data is generated manually, the challenge is the lack of standardization of the inputs. Therefore, various standardized input methods must be included in the design to enable or simplify the fastest possible utilization for the digital machine twin.

Various data characterize the digital machine twin

On the physical side, the machine is considered. Dimensions, materials used and other properties, but also meta-information such as manufacturer specifications and location can be relevant for the representation of the machine. The machine can be subdivided into modules and their components for later consideration. This can be useful if the subsystems contain their own sensors and are considered as separate use cases. In addition, on the physical side, an inventory of the various roles of the acting persons is necessary to grant appropriate data access and views later in the digital twin.

In addition to dimensions and CAD models as well as process data of the machine, which represent the machine properties, data from IT systems and models for the machine twin must also be considered. Lifecycle data can serve as an example, but also historical or planned production orders of the machine. The integration of simulations is also possible.

Production optimization through networking of machines and product

The states, properties and behavior of the machine are mapped in the digital machine twin by means of the generated database, supplementary information, and models (see Figure 6). The aggregations, which can also be enriched with information from other digital twins, are enabled in various use cases in the form of services provided by the digital twin and can thus be used. Recommendations for actions are derived from this, which can be used to optimize the machine.

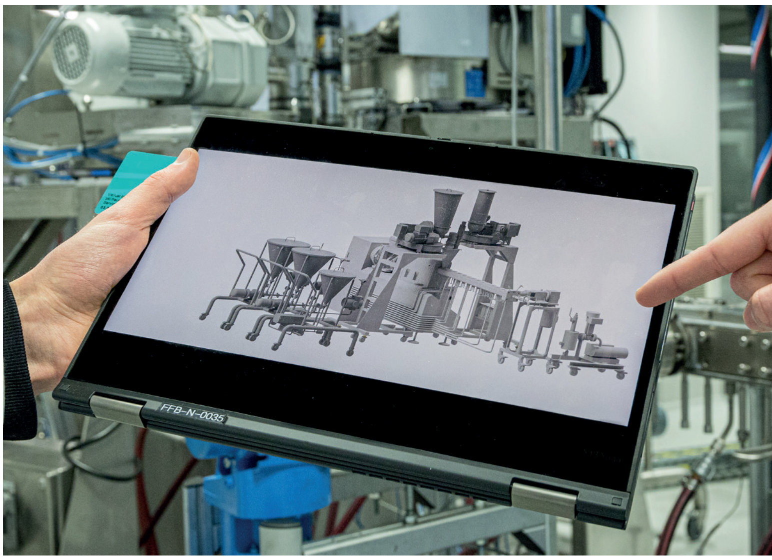
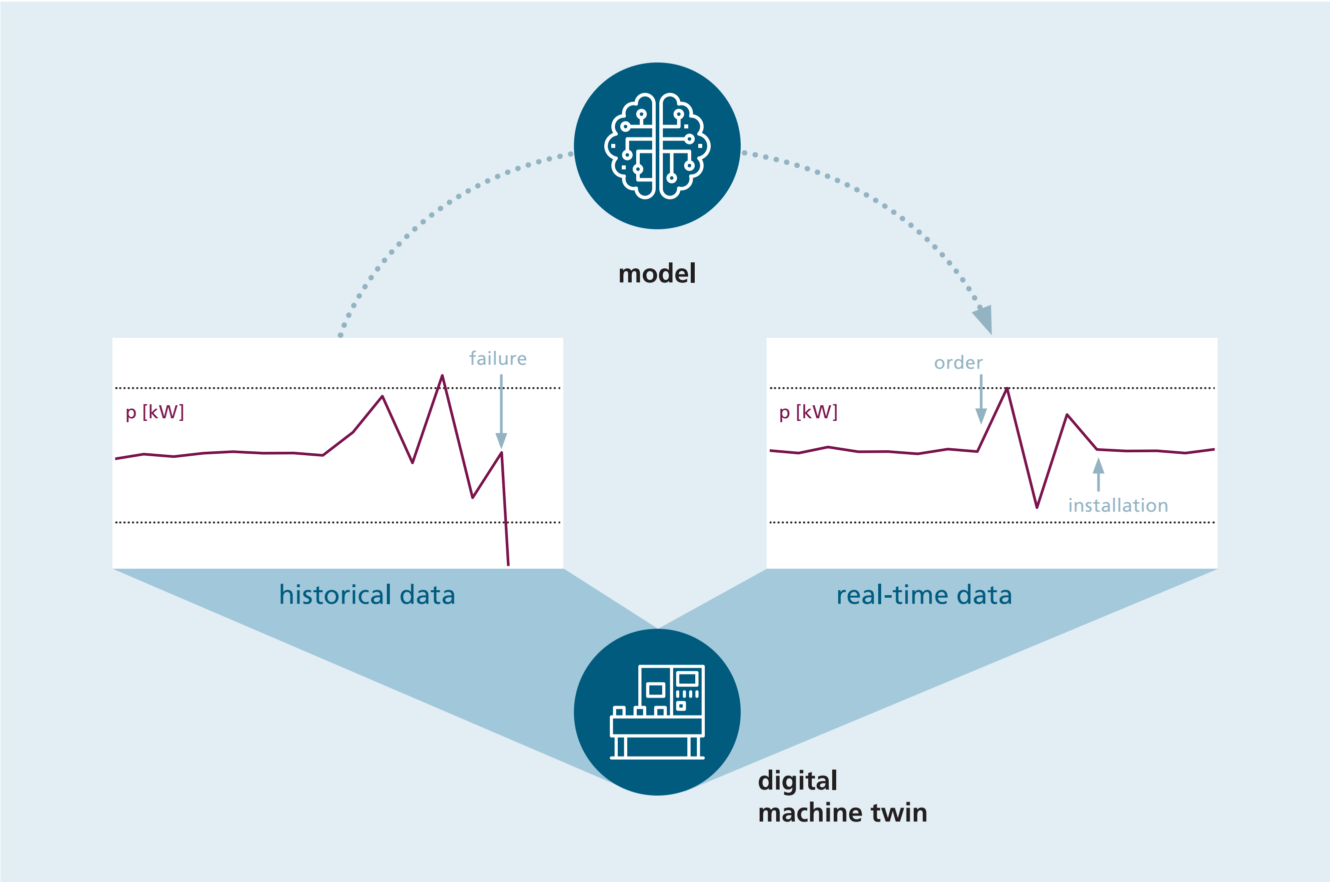


Photo above: © Studie Wiegel

The digital machine twin as an enabler for use cases — predictive maintenance

The machine twin enables predictive maintenance: Based on (historical) process data and event data on malfunctions, failures and maintenance, a model can be created that depicts the condition of the machine [49]. In this way, the condition and remaining service life of machine components can be estimated based on real-time data and a suitable model. This results in more intelligent intervals for the replacement of machine components, which can prevent expensive, unplanned downtimes and high storage costs in the future and thus increase production efficiency. At the same time — in contrast to the periodic replacement of machine components — the utilization period of the individual parts is optimized, thus saving costs, and making more sustainable use of machine components. Predictive maintenance models can therefore also be fed back into the machine twin and map the condition of machine (parts) and their remaining useful life as an exemplary aggregation of the data of the machine twin. The digital machine twin provides a suitable data basis for predictive maintenance by means of historical data and by mapping current states. A use case based on the example of the extruder's drive power is schematically illustrated in Figure 7.

Figure 7: The digital machine twin allows to predict when a new component should be ordered and installed based on historical drive power data to proactively prevent downtime



The digital product twin

Virtual representation along the entire product life cycle

Digital product twins in battery cell manufacturing enable the structured consolidation and management of data, information and models associated with a concrete instance of a physical intermediate or end product, e.g. an electrode coil or a battery cell. Descriptive and technical product data are combined and semantically linked in a global data structure. In this way, the structure and configuration of a product can be digitally mapped, enriched and linked with data on environmental influences and relevant process data. Examples include machine parameters from individual processes such as target values for the calander gap or sensor values recorded during individual production steps.

The digital product twin enables the creation of a virtual representation of the products that dynamically evolves throughout the entire process chain of battery cell production. In this way, a comprehensive traceability of the products with respect to the associated materials, manufacturing conditions and production steps is achieved. In addition to effective quality assurance through product-related findings, the systematic feedback of a product's quality characteristics with specific production parameters, for example, enables the identification of potential to improve products and processes and to continuously improve their quality. Digital product twins consider the properties of all intermediate products involved as well as process data from upstream production steps and to influence the production environment by linking them.

A special feature of the digital product twin is the large number and variety of intermediate products that must be referenced to each other. These include the electrode pastes and electrode coils for the anode and cathode, which are combined in the digital twin of the battery cell.

Digital product twins can also create added value in further phases of the product life cycle: For example, simulations based on a digital product twin can improve the efficiency of product development. Furthermore, the evaluation of usage data of the end product in combination with the stored product data can provide individual decision support for secondary utilization and recycling at the end of the life cycle, which enables a sustainable circular economy.

Information models and traceability systems as a prerequisite for the digital product twin

For successful implementation of the digital product twin, a traceability system is needed to link the data semantically and contextually. This requires an information model that is adapted to the battery cell production process and that considers both the different properties along the production process and the respective context of the data. The required information and properties include incoming goods inspections, material properties, process parameters and both offline and inline quality measurements. To build up this information model systematically, it makes sense to divide the entire production process into predefined production stages. For these steps, partial information models are then to be built, which result in the overall information model of the battery cell, when aggregated. Examples of partial information models are the digital images of the anode, cathode, or housing. The partial information models can also be used to integrate products from suppliers into the production process by transferring data in addition to the physical intermediate product. The traceability system links the data of the partial information models so that all data and information from the delivery of the raw materials to the finished battery cell can be assigned to the individual cells and made available in a context-dependent manner. For this purpose, interfaces must be defined for the end user as well as for software systems.

Complex process chains as a challenge

Tracking and tracing through the complete manufacturing process is essential for creating and using a product twin.

The greatest challenge in the implementation of the digital product twin is the traceability of the battery [50]. Correct linking and aggregation of the various data sources at different levels are essential to make reliable statements, make realistic predictions and run meaningful simulations. A high level of complexity is created by many interdependent digital product twins (subsystems), for example for intermediate products such as the electrodes, the final battery cell, or a batch of batteries. Alternating single and batch processes as well as continuous and discrete processes make it difficult to assign data to a product. Tracking and tracing through the complete manufacturing process is indispensable for the creation and use of a product twin. For example, it also plays an important role for liability issues and recalls of a final cells or batches [51]. For this reason, a comprehensive traceability system is being developed at Fraunhofer FFB.

During battery cell production, large amounts of data are recorded from the processes and quality measurements of the (intermediate) products. These must be linked in the product twin during production, as the linking of the data alone can create benefits such as the adaptive process control outlined in the digital machine twin. The product twin accesses existing databases and aggregates the information depending on the use case. The technical implementation is a central challenge, since the product twin should always be updated to provide added value — for example, through predictions. When designing the data structures, these requirements are considered and necessary interfaces are created.

In addition, the lack of standardization in the structure and semantics of the information models for a product twin in battery cell manufacturing makes it difficult to share data across company boundaries. Third-party systems must be integrated without the help of uniform standards. The first standardized technical implementations have already been designed for this purpose, such as Asset Administration Shells [52].

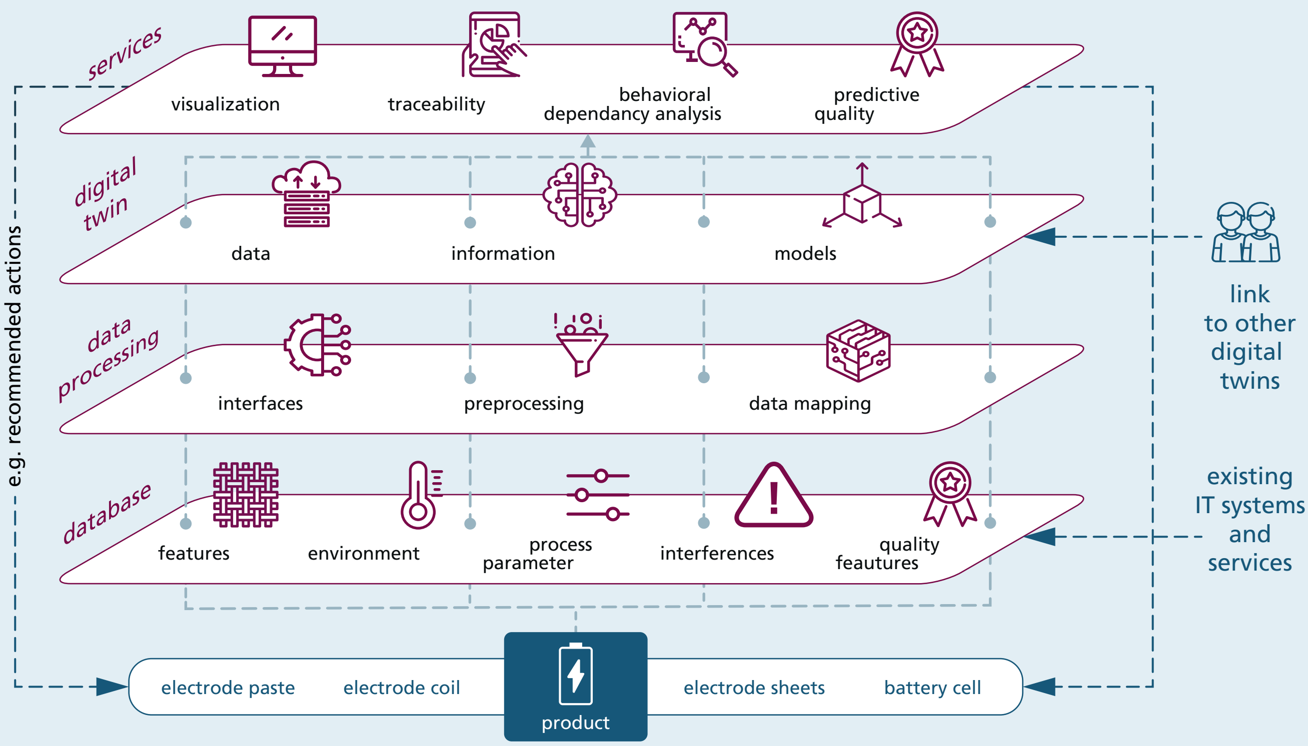
The storage and processing of the large volumes of data results in a non-negligible consumption of resources and energy.
The resulting ecological footprint must be considered when implementing the digital twin and justified by the added value. In the best case, the emission and resource savings made possible by the digital twin are greater than the emissions caused by it and a rebound effect is thus avoided. To evaluate this, methods must be developed to quantify the emissions and reductions enabled and caused by the digitization of battery cell production.

More comprehensive with each process, operational and test data

Figure 8 shows the structure of the product twin, which was developed in accordance with the understanding presented for a digital twin. The product twin becomes more comprehensive with each series of process, operational and test data. It is based on the collected data basis and is enriched with information and models. In addition to the data from the process steps, the product data also includes material data and data on the behavior of the intermediate product, so that a data basis is created to support the development of the digital twin.

Feature of the product twin is the adaptive evolution of the model, based on the current state of the product. Thus, the product twin facilitates the execution of services, for example, for product state assessment and quality management.

Figure 8: Structure of the digital product twin



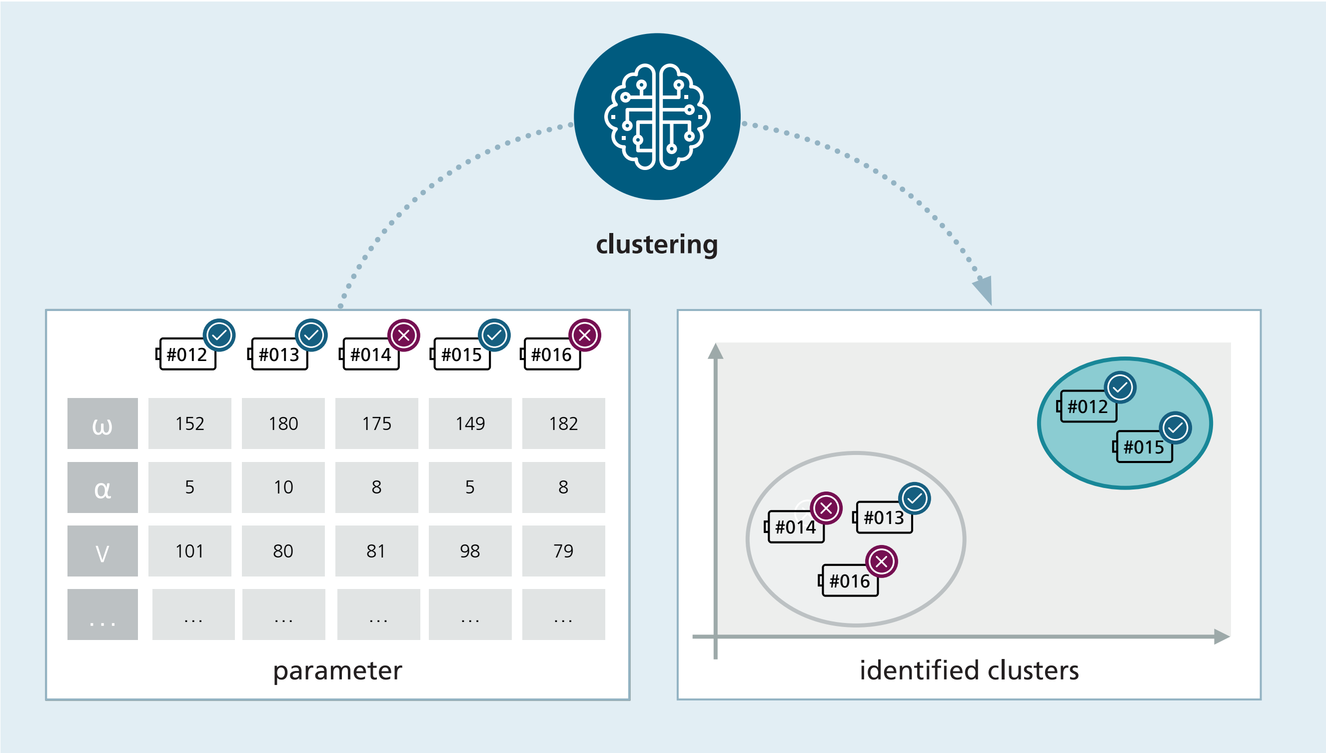


Figure 9: Use case in product development using clustering. A comparison of the quality measurements of the products in the cluster suggest good parameter configurations.

Advantages in design and production — predictive quality

One of the most important applications is the determination of product quality at crucial points in the manufacturing process. One implementation is through so-called quality gates, which enable data-based quality control at fixed decision points within the production process. Quality-related product data is collected and compared with a target value. Early detection of quality deviations allows the reduction of scrap rates. Further process steps are then not carried out on the product in the event of poor quality, thus saving time and costs. In addition to detecting failures, causes of defects can also be further investigated and categorized. Based on the cause, the process can then be adjusted to reduce scrap.

Product development and optimization

Battery cell design is another important use case in battery cell manufacturing. The digital product twin enables the structured analysis of the intermediate and end products of different cell designs and thus provides data-based decision support in the product development of new battery cells. For example, known parameters such as measured values, process parameters and recipe can be bundled. Samples of new battery cells with similar parameters are in the same cluster as outlined in Figure 9. The average quality of the clusters is compared to identify good configurations of the production parameters. In addition, new, previously unknown configurations can be discovered and tested. These configurations can then be specifically investigated and optimized.

The digital building twin

Digital twin along the building life cycle

In addition to the production, which is covered by the digital product and machine twin, the factory building also plays a central role for the digital twin of the entire battery cell production. The construction sector was responsible for almost 40 percent of the global CO_2 emissions in 2020. [53].

The construction and operation of production facilities for battery cell manufacturing cause high greenhouse gas emissions. For example, there is the need for high-performance clean and dry rooms which have high energy demands. In addition to a factory's energy requirements during operation, a large proportion of emissions are generated during its construction, for example during the production of high-emission building materials such as concrete [54]. Early planning errors often have a serious impact on subsequent stages of construction and increase costs, as well as material inputs. Estimates by the "Get It Right Initiative" in 2016 found that for every euro spent in the construction industry, up to 25 cents is lost due to design and construction errors [55].

So-called Building Information Modeling (BIM) is already often used today as the basis for optimizing construction planning and operation. The resulting 3D models can partly be equated with digital twins, but do not meet the full requirements for digital twins in battery cell production. To enable an increase in efficiency and thus cost, as well as a reduction of emissions of the factory building, it is important to simplify the communication between the involved contractors as well as to aggregate and preserve data and information throughout the life cycle of a building, as shown in Figure 10. For battery cell manufacturing, this means that opportunities for a variety of optimizations and efficiencies can arise through the use of the digital twin during the life cycle of the building.

Inaccessible data from different contractors

In addition to the cross-domain challenges that arise during the design and implementation of any digital twin, there are several other characteristics related to the building twin that need to be considered.

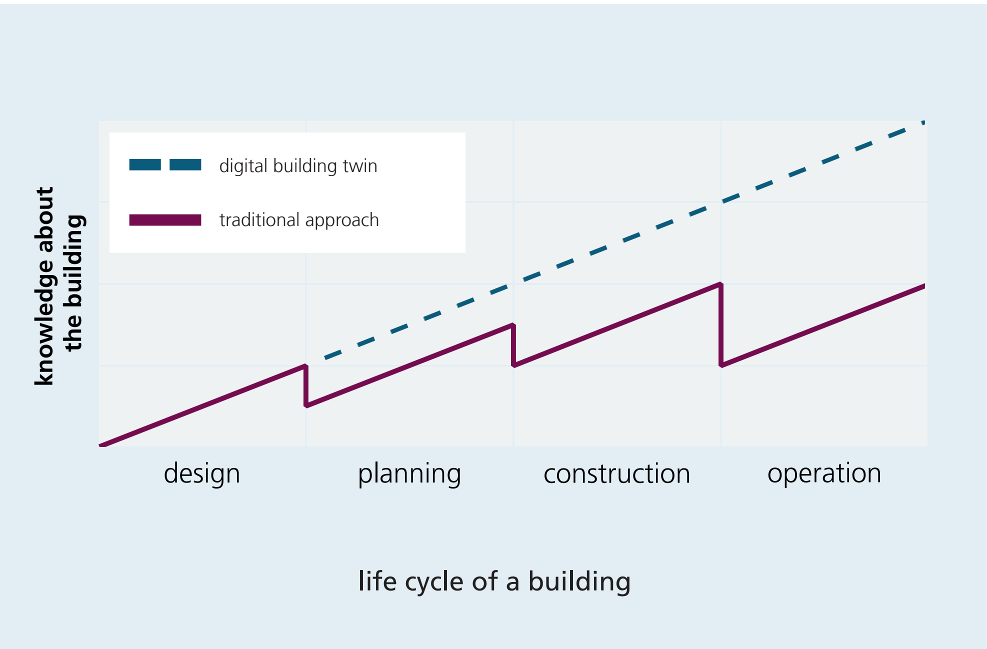


Figure 10: The available knowledge about the building during its life cycle. During the transition between the different phases, a high loss of information takes place in the traditional approach. (Adapted from [56]).

The digital building twin enables optimization and efficiency improvements in the different phases of the factory building life cycle.

One of these characteristics arises from the multitude of partners involved in the construction and operation of complex buildings such as factories. From initial ground surveys to architectural design to handover and operation of the building, a single major project can easily involve dozens of different companies. Not all relevant information is always available to all stakeholders during the process. While this is where the great potential of the digital building twin as a one-stop shop for all building-related data becomes apparent, it is also one of its greatest challenges.

During operation, the interconnection of the various building components and systems is of high importance. Not every system is "smart" and provides its data by a freely accessible interface. This also applies to actuators such as shading systems or ventilation systems, which cannot always be controlled centrally and therefore be represented by the digital twin. Furthermore, not all types of data can be collected automatically. Compared to the digital product twin, a large amount of information regarding defects, remodels, maintenance, or repairs must be collected and updated manually. This is prone to errors and jeopardizes the digital twin's claim to always be an exact replica of its real counterpart. Standardized procedures therefore need to be defined for such non-digitized processes.

Synergies between existing systems

To date, there is no uniform definition of the various components of a digital building twin [57]. Nevertheless, some functionalities can be identified in the building domain without which the implementation of a digital twin is not feasible. In particular, these include the following, which are described below:

- Life cycle spanning platform for information exchange
- Structured, up-to-date and consistent database
- Representation of the actually constructed state (as-built model)
- Building automation
- Communication interface between shop floor and factory building

Digital platforms for exchanging information are already being used in the BIM context in the form of so-called common data environments, thus facilitating collaboration across trades in the early life phases of the factory. However, a prerequisite for sustainable factory operation is to establish comparable exchange platforms for the other life phases as well, to guarantee access to the information for all stakeholders.

Once a holistic exchange of information has been technically implemented, it is the task of the digital building twin to act as a structured, up-to-date, and consistent source of data. In addition to the continuously updated building data, historical data such as floor layouts, or planning documents must also be integrated. In order to avoid a loss of information during building handover, for example, the planning and construction information must be provided to the building's operator in a manageable way.

Part of the up-to-date data must also be an as-built model of the factory building, i.e., 3D models that document the actual condition of the structure after construction. This not only improves quality and defect management during the construction phase, but also supports the operator after completion of the building by providing the ability to visually locate parts of the building in an exact way.

To ensure efficient and safe operation, building automation is also an important component of the digital building twin. However, controlling, regulating, and optimizing the technical building equipment in isolation is not enough in many cases. For example, holistic energy management in battery cell production requires the interaction of different building and production components. This requires an interconnection between the highly complex machine technology and the building. Standards and norms must therefore be developed and used to ensure compatibility and interoperability — i.e., communication, data exchange and documentation across heterogeneous information sources — between the individual, often proprietary systems.

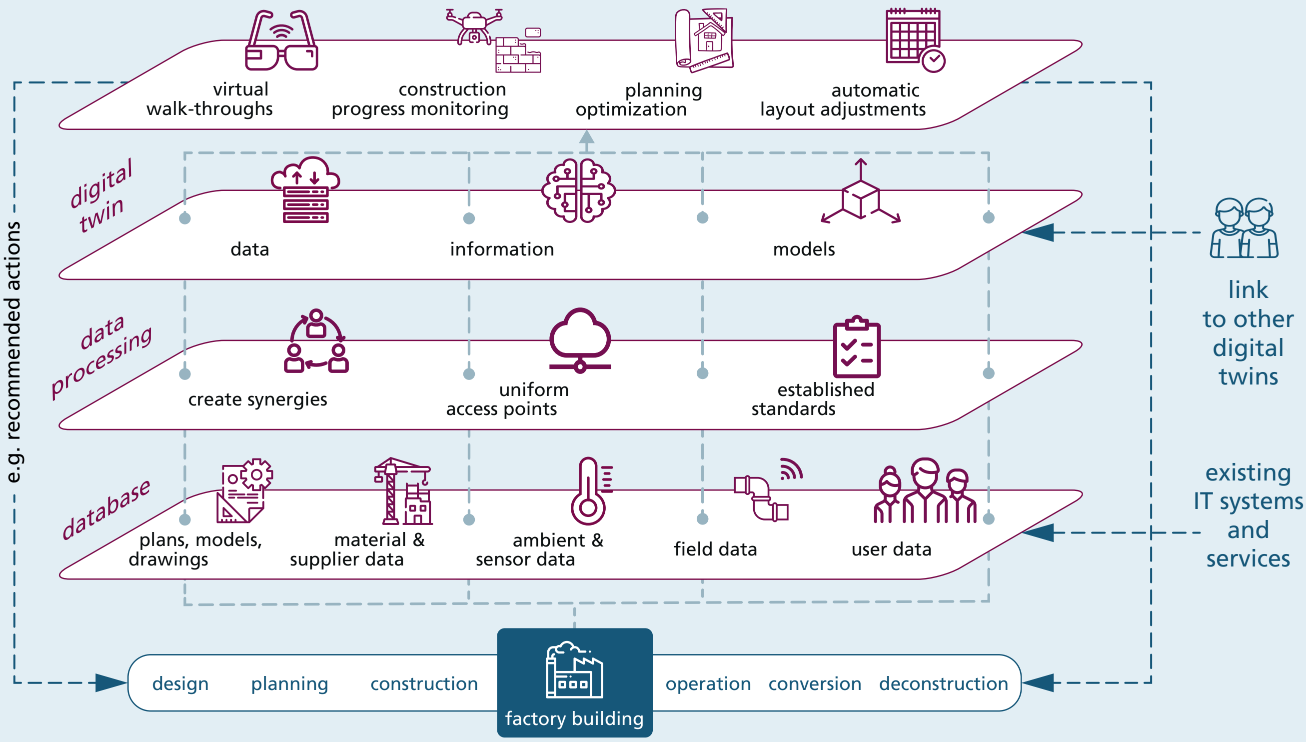


Figure 11: Structure of the digital building twin

The goal of the digital building twin is to create synergies between the already existing but partially stand-alone systems, to reduce complexity in the heterogeneous system landscape by means of standards, to provide standardized access points and role-based user interfaces, and to provide additional knowledge with measurable added value.

Networking of building and production

Figure 11 shows the relationship between the factory building in its physical representation and the digital building twin. Building on the factory itself as well as plans, technical drawings and 3D models used in the early lifecycle phases, the dataset is expanded continuously to include additional data sources.

In conjunction with the existing IT systems, the basis for more in-depth analyses and evaluations is therefore created. However, data processing is essential to extract information from the raw data and to derive knowledge at later stages.

If uniform access points with clear role definitions are provided and standards are integrated into the data processing process, different services can be offered, enabling the interconnection of buildings and production.

Added value of the digital building twin during planning, construction, and operation

The added value of the digital building twin is demonstrated along the life cycle of the building using concrete use cases during the planning, construction and operation phases:

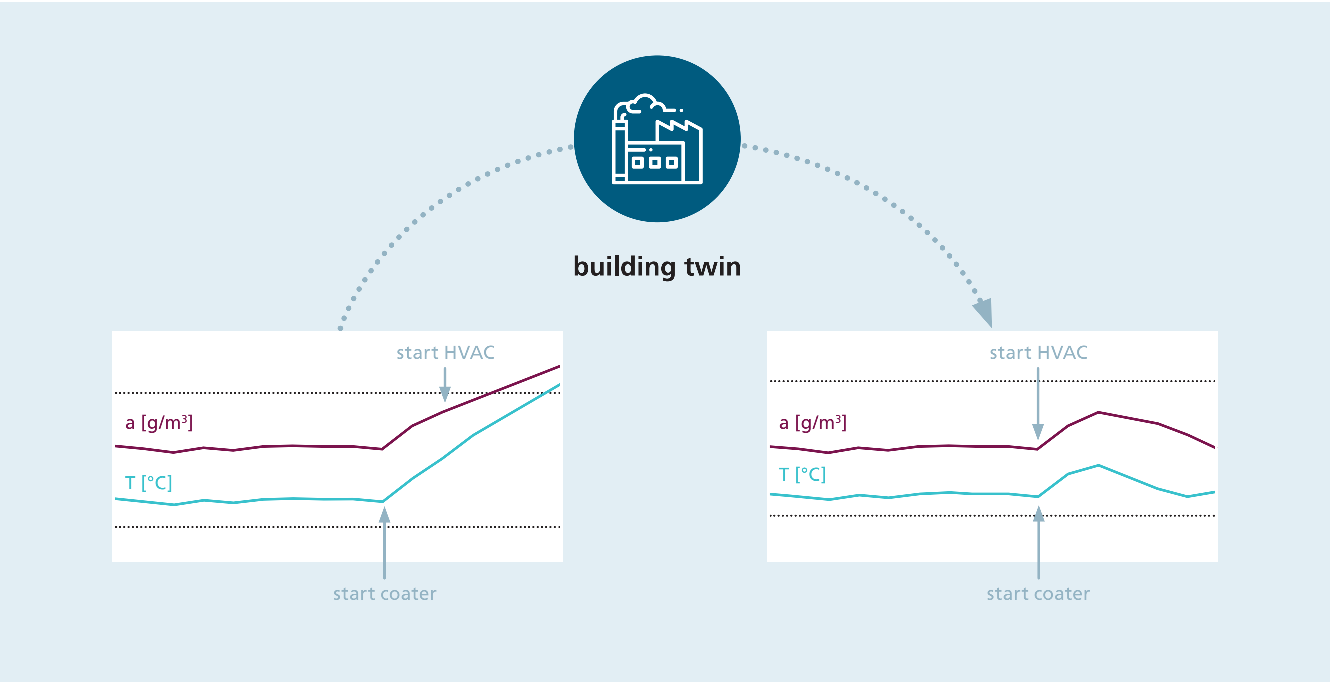
- Planning

In planning, the digital twin can serve as a starting point for easier coordination and information exchange between project partners. This can optimize the planning process and reduce the probability of errors resulting from the interaction of different trades. Realistic simulations can be carried out on the basis of the available data from the digital twin. This makes it possible to dynamically evaluate the effects of necessary changes in the planning, for example caused by required cost savings, on the entire building. In addition, the future factory operator can view the current status of the planning at a central location at any time. This creates transparency, and late change requests from the client can be more easily taken into account. For example, the digital twin can be used in the planning of a construction project for change management, such as in the floor planning and layout of logistics and production areas. During the planning process, various changes to the building may occur. These changes have a direct impact on the availability of floor space, dimensions of the various production areas, and how they can be used. For example, special fire protection regulations for storing battery cells and raw materials must be taken into account. The digital twin can help to process the information about new changes and transfer it to a layout planning tool, where it can optionally support the selection of the best layout by means of simulations.

- Construction

Similar to the planning phase, the digital building twin serves as a central point of contact for all partners and contractors involved in construction. Dependencies between the trades can be reliably displayed and processes can be optimally planned. The continuous comparison between the planning and the actual construction progress enables all involved parties to recognize errors or deviations promptly. Additionally, they can be predicted and therefore enables the stakeholders to be able to intervene a flexible and targeted manner. With the help of 3D scans, this comparison can be partially automated.

Figure 12: The digital building twin enables predictive building control to reduce peak loads and deviations in product quality



During the construction phase, the digital twin can be used, for example, to monitor the condition of the materials used. It is used to analyze whether all materials are available and where these materials are located. In addition, it can be used in the ordering process to calculate the optimal cost point for an order.

- Operation

The large volumes of data, aggregated in the digital building twin during design and construction, are fully available to the operator of the building at the time of handover. This closes a previously common knowledge gap and facilitates smooth handover and commissioning of the building. The current state of the building is mapped in all its facets at all times by the digital building twin. This simplifies, for example, the adaptive control of the building, the optimization of energy requirements and the coordination of maintenance work. In contrast to established systems, many different data sources are linked and correlated here. In the case of extensions or remodels, a solid data basis from the entire history of the building is available, which can accelerate planning and execution.

A concrete application from the operating phase of a factory building is the early and predictive conditioning of dry and clean rooms. In the event of predictable deviating conditions, such as an additional influx of moisture due to maintenance work on the production facilities, the dry room technology can be automatically adjusted at an early stage on the basis of historical data and this new information (Figure 12). In this way, the energy requirement can be reduced with a view to peak loads and continuous compliance with the required ambient conditions can be ensured.

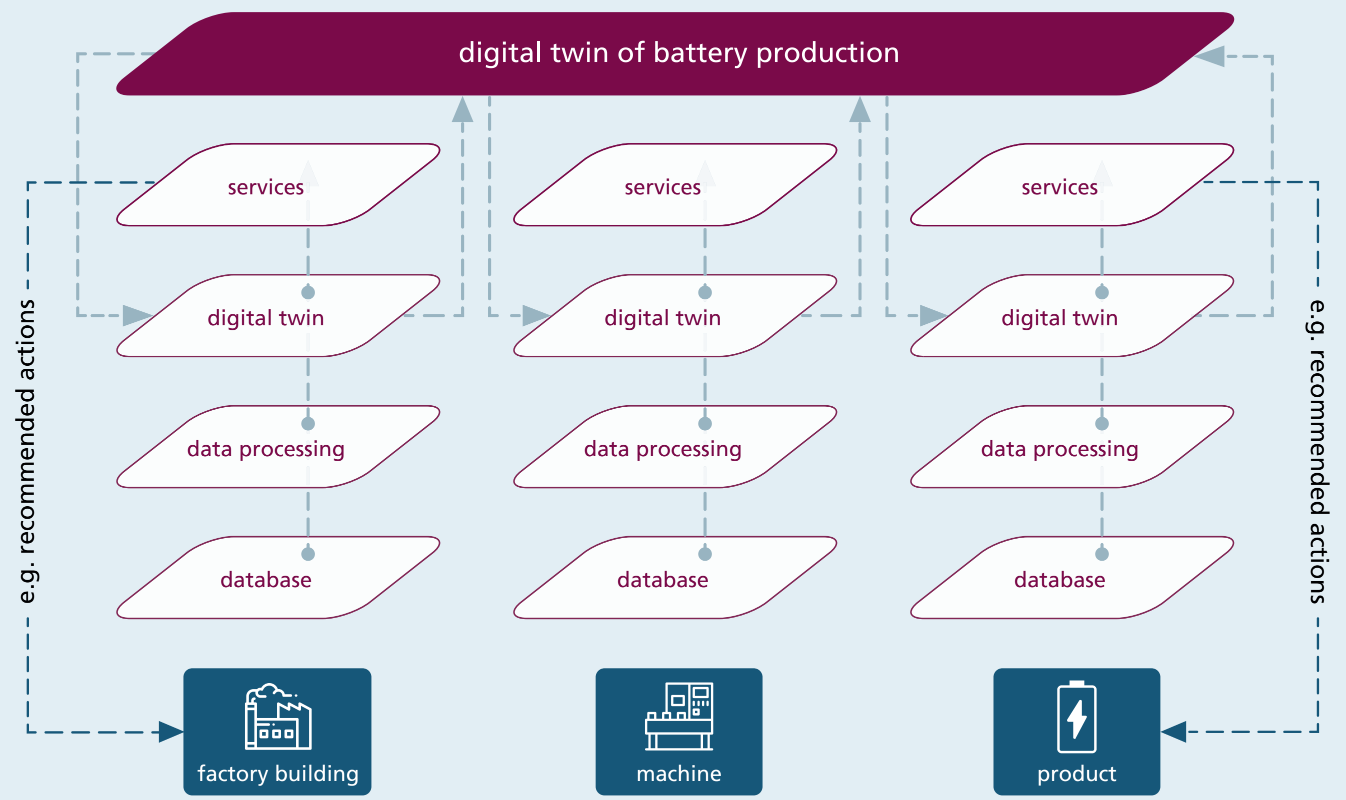
The digital twin of battery cell manufacturing

The digital twins of the machine, product or building offer different services and benefits. In addition, there are use cases in which the various forms of the digital twin must be considered in combination. This is brought together in the digital twin of battery cell production, which uses standardized interfaces to access the subordinate digital twins and create a comprehensive exchange of data and information.

The digital twin of battery cell production corresponds to a higher-level module of digital machine, product and building twin, through which modularization is achieved. The modular structure reduces complexity and facilitates manageability at the technical level. New functionalities, for example based on new sensor technology, can be implemented in an uncomplicated way so that all resulting data and information are available to other applications. Furthermore, unforeseeable conceptual changes to the building, product or machine can also be considered in the digital twin of battery cell production by simple adaptation in the corresponding module. This flexibility in design allows the digital twin to be transferred to other battery manufacturing sites and implemented there.

Networking the individual forms of expression to form a digital twin of battery cell production opens up further opportunities to increase both sustainability and efficiency. Questions regarding energy requirements can be answered by information from the machines and the building. Particularly, when considering the operation of the dry rooms

Figure 13: Interaction of the various forms of digital twins.



associated with the digital building twin, there exists a strong dependency on production. This represents a clear and necessary interface between the digital machine twin and the digital building twin. Furthermore, the product quality is strongly influenced by the machine settings and parameters, such as the slot die settings of the coater in the electrode production on the layer thickness of the electrode foil. For an analysis of the cause-effect relationships, machine data from the digital machine twin must therefore be linked with quality data from the digital product twin. The creation of the so-called "Battery Passport" (see following section) also requires the linking of all forms of expression. Figure 13 schematically shows the interaction of the different forms. In the superordinate digital twin of battery cell production, the digital twins of machine, product and building are accessed and information, data and models can be viewed together.

Battery passport and improved life cycle assessment

The "Battery Passport" is an electronic file for each individual battery and contains dynamic battery data that accumulates during the life cycle of a battery. This data is stored centrally. This includes general information on the battery type, data from battery cell production, but also the CO_2 balance, usage data and data on suppliers [8, 58].

The digital twin of battery cell manufacturing makes it possible to create a "Battery Passport", as the required data is already aggregated in a central access point. The data from the digital twin at cell level can be aggregated at battery level and transferred to the "Battery Passport" in accordance with the regulation. This can be, among other things, the product data from the digital product twin, the manufacturing parameters from the digital machine twin or the consumption data from the digital machine and building twin.

With the help of the digital twin of battery cell manufacturing, a Life Cycle Assessment is made possible. In this way, the energy balance required for the "Battery Passport" can be reported. Life Cycle Assessments also create transparency about the current sustainability level of a product or production by indicating the CO_2 footprint.

Use cases of the digital twin of battery cell manufacturing — adaptive process control

Adaptive control of the process, based on the quality of the intermediate and/or final product, is an example of how different digital twins can add value in combination: Adaptive process control allows optimization of process variables, based on the quality of the output (for example, the residual solvent content after drying). For this purpose, current parameters of the machine, such as the temperature of the heating system, are related to the current production quality of the products, based on the data of the product twin. For this purpose, cause-effect relationships between the various influencing, process and quality parameters have already been determined during the "FoFeBat)" project (cf. [59]). From this linkage, a model can be created that suggests recommendations for the process parameters to be set, which can improve production quality or be used for automatic control.

The parameters can be derived based on the digital product twin and through external IT systems that perform production planning. The utilization of the machine can thus be deliberately controlled by connecting IT systems but also by communicating with other digital twins. In addition to the product twin, machine twins of the respective previous and subsequent process step can also be used. Adaptive process control enables more efficient processes with increasing quality. This in turn reduces the costs of production.

By connecting the different digital twins, the greatest added values are leveraged along the entire production.

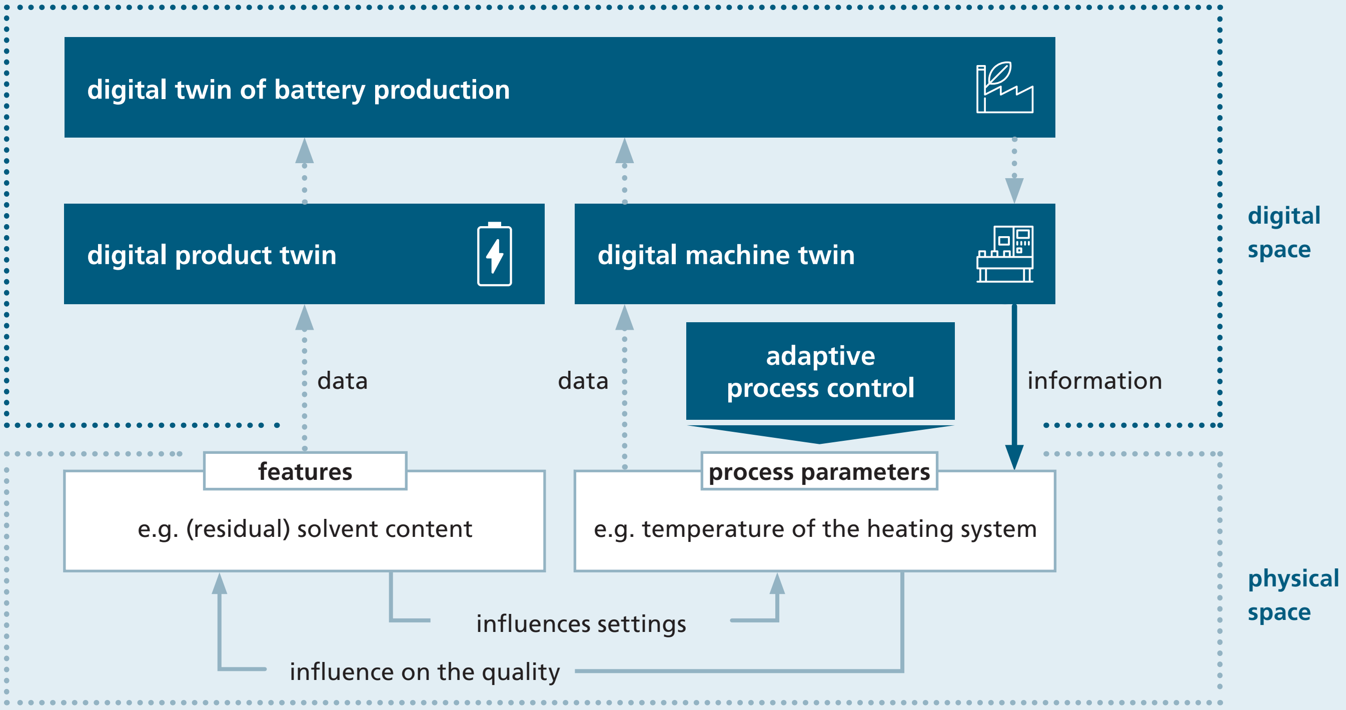


Figure 14: Adaptive process control allows the temperature of the heating system to be adjusted during the drying process, based on current quality characteristics of the manufactured products

Figure 14 illustrates adaptive process control using drying as an example [51]. The temperature of the heating system is set based on current quality characteristics of the manufactured products, represented here by the residual solvent content. Data, such as the initial solvent content of the electrode paste, from the digital product twin can be used and the temperature of the heating system can be adjusted via the digital machine twin, so that the quality is optimized.

The implementation of the digital twin at Fraunhofer FFB

The digital twin in battery cell production sets the fundament for an economically and ecologically optimized factory. At the same time, the digital twin can be the basis for further applications, research, and development projects along the life cycle of the battery cell [51].

As part of the "FoFeBat" project, a definition of the digital twin in battery cell manufacturing was derived based on the scientific discourse to date and adapted to the use case. Since battery cell manufacturing holistically involves interdisciplinary tasks, a uniform understanding of all aspects — such as the necessary components, the objective, or the benefits — must first be developed and implemented. The identification of the forms allows the measures to be specified in the various use cases and leads to the generation of the digital twin for the entire factory. It interacts with the individual digital twins from different domains to enable sustainable production of the battery cells.

As part of the "Forschungsfertigung Batteriezelle (FoFeBat)" project, the conceptual design of the individual digital twins was initiated. The implementation of prototypes in the respective forms is planned for the near future.

The integration of the twins from various domains into Fraunhofer FFB production scenarios is then implemented to optimize battery cell production based on the digital twin. Maturity models will be developed during the project for the conceptual design and implementation of the digital twins to ensure the highest possible level of uniformity and reproducibility.

In the light of advancing climate change, the digital twin can help enable more sustainable production by reducing waste, increasing product quality, and optimizing energy consumption. The use of a digital twin — from raw material through cell manufacturing and first life to remanufacturing or recycling — can also improve the life cycle assessment of batteries. The digital twin can also make a decisive contribution in the future to fulfilling Act on Corporate Due Diligence Obligations in Supply Chains [9], which has already been passed by the German government, and to the creation of a "Battery Passport" as part of the Green Deal [60] envisaged by the European Union. Depending on the use case, the benefits will manifest in every lifecycle phase. Due to the transparency of production created, it allows the rebound effect caused by the increased use of digital technologies to be controlled.

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Editorial notes

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- Fraunhofer Institute for Manufacturing Engineering and Automation IPA
- Fraunhofer Institute for Factory Operation and Automation IFF
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- Fraunhofer Institute for Solar Energy Systems ISE
- Fraunhofer Institute for Chemical Technology ICT
- Laboratory for Machine Tools and Production Engineering (WZL) of RWTH Aachen
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Photo acknowledgements

Cover photo, page 2/3: deepagopi2011 – stock.adobe.com
Page 15 (photo above), page 18 (left photo): Studio Wiegel
Page 25, Page 29: ARTVISU Artur Krause

DOI

10.24406/publica-495

This publication was produced with the collaboration of:

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Publisher

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