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Material Flow Simulation in Lithium-Ion Battery Cell Manufacturing as a Planning Tool for Cost and Energy Optimization

Maximilian Lechner[1], Paul Mothwurf[1], Lasse Nohe[2], Rüdiger Daub[1]
[1]Institute for Machine Tools and Industrial Management, Technical University of Munich, 85748 Garching, Germany
[2]Northvolt AB, Alströmergatan 20, Stockholm, Sweden

Abstract

Lithium-ion batteries are seen as a key technology for powering electric vehicles and energy storage. Still, their high cost and energy-intensive manufacturing process remain a significant barrier to wider adoption. Due to the high moisture sensitivity of certain processed materials, the operation of dry rooms is required, constituting a critical contributor to cost and energy consumption in lithium-ion battery production. As the operating costs for these dry rooms strongly depend on the volume and adjusted humidity of the air, it is vital to choose an appropriate operation strategy already in the planning and designing phase of the factories. In this regard, simulation tools can effectively support the planning process by providing predictive information on the production system. The simulation model presented in this paper offers an approach to optimize the material and energy consumption associated with the production of lithium-ion batteries while also considering current material-related production challenges regarding moisture. By calculating a time-resolved material flow, the model enables to identify individual process times and storage durations depending on the chosen production layout. This allows for a material-specific dimensioning of the buffers and supports the dry room design. Hence, the data generated by the model can serve as a basis for planning more cost- and energy-efficient production environments.

Keywords

lithium-ion battery; battery production; material flow simulation; gigafactory; dry room; moisture sensitivity; production planning

1. Introduction

As the global drive towards mitigating climate change intensifies, the need for sustainable energy solutions has become more critical than ever. Lithium-ion batteries have emerged as a pivotal technology, powering a wide range of applications such as electric vehicles, grid energy storage, and portable electronic devices [1]. However, the increasing demand for these batteries requires cost-efficient production methods to ensure their widespread adoption and affordability [2]. In this context, the establishment of gigafactories – large-scale production facilities for battery cells – has gained significant importance. These factories play a central role in meeting the soaring market demand, reducing production costs through economies of scale, and promoting the transition to clean energy alternatives [3,4]. A conventional lithium-ion battery cell, comprising a cathode, an anode, a separator, and a liquid electrolyte within a protective housing, is produced in multiple successive process steps (cf. Figure 3) [2]. In this regard, a major challenge is the requirement for moisture control within the production environment, as the production involves processing moisture-sensitive materials like nickel (Ni)-rich cathode active materials or electrolyte materials [2]. Excessive

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humidity can entail safety hazards during production and harm the battery quality, leading to losses in capacity, lifetime, and overall performance [5,6]. To mitigate these risks, controlled atmospheres in the form of dry rooms are commonly employed to maintain optimal humidity levels during various production stages [7,8]. With regard to the energy consumption in lithium-ion battery production, it can be stated that dry rooms account for about 30 to 50 % of the overall energy consumption [1,9,10]. When looking at the energy consumption of an exemplary dry room, it becomes apparent that it strongly depends on the adjusted humidity level and the number of persons in the room [11]. These relations are depicted in Figure 1 and underline the dry rooms' significant impact on operational costs. Therefore, the design and implementation of such dry rooms must be carefully planned to ensure energy- and cost-efficiency while also considering material-based requirements. To address these challenges, a comprehensive and systematic approach for designing the production layout and dry room facilities is essential. In this endeavor, material flow simulation models like digital factory twins emerge as valuable tools, enabling the calculation of throughput-specific data like lead and storage times for various production layout alternatives. The model presented in the following allows for considering both material- and production-related requirements and serves as a basis for an optimization approach for dry room design and operation in gigafactories.

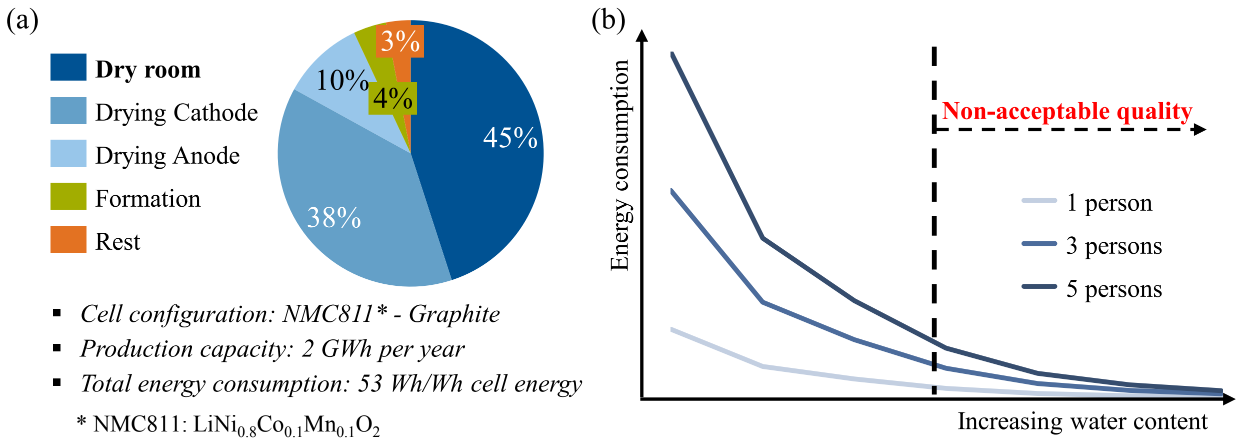

Figure 1: (a) Distribution of energy consumption between process steps in lithium-ion battery production according to [10] and (b) qualitative relation of energy consumption in dependence of humidity level and number of persons in the room for an exemplary dry room [11]

2. Background & Approach

With regard to the current material trends for lithium-ion batteries, Ni-rich cathode active materials play a major role. By increasing the Ni share in the cathode active material, higher energy contents can be achieved. Besides that, social aspects can be addressed when substituting the critical and expensive raw material cobalt, which is currently widely used [12]. The progression in state-of-the-art cathodes went from Ni shares of around 30 % to over 80 % today, with further increasing Ni contents [13,14]. However, the increased Ni shares impose higher requirements on the production atmosphere as Ni-rich active materials are susceptible to moisture (H_2O) and carbon dioxide (CO_2). When in contact with the ambient atmosphere, the particle surface can form impurities by reacting with H_2O and CO_2, leading to lithium-ion consumption. Consequently, losses in capacity, rate capability, and lifetime occur, which are influenced by the moisture content and exposure time [8,15–17]. For that reason, high-quality Ni-rich cathodes require production under low humidity levels, which can be realized in dry rooms with controlled environments [12]. Figure 1 (b) indicates that for a cost- and energy-efficient production, the humidity level of the dry room should be kept as low as possible. However, due to uncertainty regarding the required dryness levels, drying units tend to be oversized to ensure that the cell quality is not negatively affected, resulting in significantly increased energy consumption and operational costs during cell production [18]. Consequently, this work aims to establish an approach that supports practitioners to identify an efficient individual moisture management strategy, which is detailed in the following.

In this regard, Figure 2 shows an overview of the methodological approach and highlights the role of the digital factory twin.

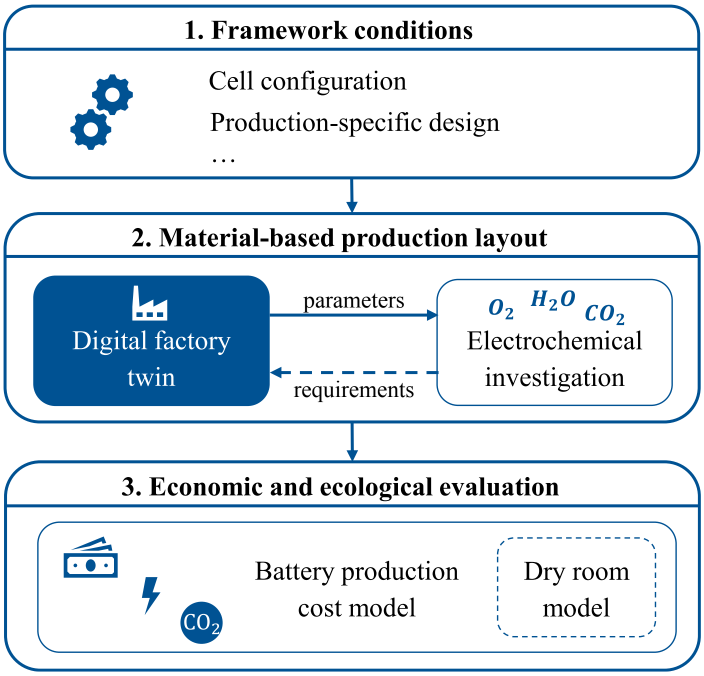

Figure 2: Overview of the methodological approach for optimizing dry room design and operation and the integration of the digital twin

The concept consists of three stages and starts by setting the framework conditions. Here, the cell configuration, including cell format and chemistry, must be determined to select an appropriate process chain. This step also requires the specification of factory-related variables like production capacity, operation days, machine availabilities, and buffer sizes. In the next stage, a suitable production layout can be identified based on material- and process-specific requirements using the digital factory twin. Based on the framework conditions, the latter enables the calculation of individual storage and lead times, which is essential for considering material-specific requirements. Knowing the exposure times of the intermediate products along the production process chain, targeted material-based experiments can then be conducted to evaluate the sensitivity toward a specific environment. In that way, the impacts on the material can be identified so that the production layout can be adjusted accordingly using the digital factory twin. By changing critical parameters like buffer sizes, number of machines, and dry room design, the model enables to quickly adapt to an appropriate production layout in terms of moisture management. To evaluate the adjusted production layout from both an energy consumption and cost perspective, a combined calculation model can be used. This model, which is part of the last stage, comprises a battery cell production cost model and a dry room model that is able to represent the framework conditions of the dry room design and operation.

3. Material Flow Simulation Model

3.1 Digital Factory Twin

Digital twin technology has emerged as a significant enabler for the production sector, offering substantial benefits [19]. In this context, a digital twin refers to a virtual depiction of a physical production system, though no single definition exists here [20]. In lithium-ion battery production, rapid development and uncertainty during factory planning can increase costs. Employing a digital twin in early design stages enables accurate production estimation and concurrent development between product design and factory planning, addressing these challenges. For the herein-presented digital factory twin, discrete event simulation (DES) is chosen as a suitable tool to model the complex battery cell production system. In this regard, the platform Tecnomatix Plant Simulation (PlantSim), established by the company Siemens, is selected since it supports flexible large-scale simulations, enabling users to quickly simulate complex scenarios [21].

A central aspect of factory planning involves determining the optimal size of material buffers situated between the individual process steps. These buffers impact the factory design and space requirements, substantially influencing operational expenditures (OPEX). This is primarily because most processes must be conducted within environmentally controlled dry rooms with heightened energy consumption demands, as stated above. At the same time, the buffer sizes also have an impact on the exposure times of the individual materials to the specific environment. This circumstance allows to adapt to material-specific requirements by adjusting the production system. So, the purpose of the digital factory twin is to facilitate the evaluation of material buffers between individual processes to enable appropriate dimensioning as well as an accurate prediction of the space requirements.

3.2 Modularization & Simulation Logic

The production of lithium-ion battery cells comprises a high number of sequential and interdependent process steps, leading to increased complexity [22]. Hence, for expedient modeling, it is crucial to capture the characteristics of the process steps in terms of their interaction with the buffer. This requires a thorough depiction of the processes and their material throughput, whereby the general calculation principle is based on previous publications [23,24]. Table 1 shows the considered processes for the calculation classified as modules, including the general and throughput-specific input parameters. The *splicing* and *slitting factor* accounts for optional foil separation that might be implemented in continuous process steps. Regarding the modules, it needs to be mentioned that the cell assembly consists of several individual process steps. However, as the focus is on electrode production, cell assembly is modeled as a single process without any internal buffers. Additionally, to expedite simulation time, the cell assembly is modeled batch-wise, described by the parameter *batch size*. Besides the direct material-throughput parameters, also general machine parameters are considered that indirectly influence the throughput. Here, the yield defines the variable scrap rate, whereas the performance indicates the machine's processing speed relative to the maximum possible speed. This factor can be used to synchronize anode and cathode processes for balanced buffer stocks and is particularly used for the coating process. The availability considers machine downtimes due to defects or maintenance work and specifies the available processing time of the machine. In this regard, the mean time to repair the machine and the auxiliary process time, which indicates set-up times, is also considered to enable more realistic modeling. Therefore, by additional consideration of blocked and idle machine times during production in combination with the machine-based parameters defining the overall equipment effectiveness, the individual process efficiencies can be determined. The process efficiency indicates the utilization and output yield of all machines in the respective process step.

For a rapid and efficient parametrization, the digital factory twin incorporates functions that automatically update all module parameters, including equipment and buffer settings, based on input tables. These input tables enable a centralized adjustment and examination of different production layouts and designs. By that, it is possible to adapt to material and production effects seamlessly. The required data tables comprise product-related information like the electrode design and dimensions, process-related data like process and machine parameters, and production-related settings like the buffer and machine counts. The latter are used in a line balancing function, which autonomously places and connects the machines based on the input table. Line balancing aims to efficiently operate the machines while reducing the product's lead time. For an efficient component routing between the modules, individual process plans for cathode, anode, and jelly roll (cell body consisting of anode, cathode, and separator) handling need to be defined. This allows to consider the unique properties of the components and enables their appropriate handling by independent material flow. For smooth inter-module movement, the modules provide feedback on production availability and buffer space for component transfer. This feedback is crucial in ensuring efficient component flow through the production process. In the simulation, a function is implemented that controls the transport of the components after successful processing, whereby the process plan specifies the target module but not the specific station. To ensure even distribution and minimize bottlenecks, individual stations request components as soon as they have the capacity, guaranteeing movement to unoccupied stations.

Table 1: Modules and required input parameters of the PlantSim model

Module	Input parameters	
	Throughput-specific parameter	**General parameter**
Slurry mixing (Cathode/Anode)	Mixing time / l_{Batch}/min	Yield / % Performance / % Availability / % Auxiliary process time / s Mean time to repair (MTTR) / min Minimum/Maximum of MTTR / min
Coating (Cathode/Anode)	Coating speed / m/min Slurry usage / kg/m Splicing/Slitting factor / $-$	
Slitting (Cathode/Anode)	Slitting speed / m/min Splicing/Slitting factor / $-$	
Calendering (Cathode/Anode)	Calendering speed / m/min Splicing/Slitting factor / $-$	
Post-drying (Cathode/Anode)	Drying time / h Number of coils per chamber / $-$	
Cell building – Winding/Stacking	Cells per minute / $parts/min$ Anode/Cathode/Separator foil length / m Number of anode/cathode sheets / $-$	
Cell assembly	Assembly speed / $parts/min$ Batch size / $-$	

4. Case Study – Impact of buffer sizes

A short case study is presented in the following to demonstrate the possible applications of the digital twin model. For that, two scenarios are compared, which should show the applicability of the model for evaluating storage durations of specific cathode materials. The simulation duration was set to 17 days, with the initial three days designated as a tuning phase to fill the buffers and machines and to ensure a smooth process start [25]. Data capture and recording started after the completion of this tuning phase, considering the required ramp-up times of the machines to stabilize. Hence, the results represent a production run of 14 days.

4.1 Scenario

For the modeling of the material flow, first, the battery cell has to be defined. A state-of-the-art lithium-ion battery cell, currently deployed in the automotive industry, with $LiNi_{0.8}Co_{0.1}Mn_{0.1}O_2$ (NMC811) cathode and graphite anode, is chosen for the case study. The areal cathode capacity is set to 5 mAh cm^{-2}, considering specific capacities of 200 mAh g^{-1} for the cathode active material and 360 mAh g^{-1} for the anode graphite material [12,13,26]. As cell format, a tabless cylindrical cell type "4680" is assumed so that a winding process is considered. The cell housing dimensions are chosen so that an overall energy content of about 84 Wh is reached, aligning with current benchmark studies [27].

The assumed process chain, depicted in Figure 3, considers coating and drying as one integrated process step. For the cathode, the slitting is conducted before the calendering due to the risk of wrinkles, which affects the tabless cell design quality [28]. The modeling ends with the cell assembly as the last module since the focus here is on electrode production and its intermediate products. Overall, the factory is designed with a production capacity of 16 GWh per year, based on the maximal output of the considered coating process and assuming an operation over 24 hours per day and 365 days per year for a simplified plan machine occupancy of 100 %. The related machine, process, and production parameters are summarized in Table 2 in the Appendix. The individual material buffers are located between the process steps so that, in total, five buffers are integrated for the electrode production, comprising slurry, coated coils, slitted coils, calendered coils, and post-dried coils. To showcase the effect of different buffer sizes on the storage durations, two scenarios are compared. For that, the buffer sizes are dimensioned based on the individual inventory coverage (IC) and the potential material throughput of the coating process (TC). Hence, the buffer sizes (BS) correspond to the same cell amount and are calculated as follows [29]:

$$BS = IC \cdot TC \tag{1}$$

As inventory coverage, 8 hours (representing one shift) and 24 hours (representing one working day) are chosen. This means that when the buffers are entirely filled, production could continue at least for this amount of time in case of, e.g., material shortages or delivery delays. This ensures the desired cell output since the production capacity and required cycle time are based on the material output of the coating and drying process due to the high investment costs and area footprint associated with this process step [3].

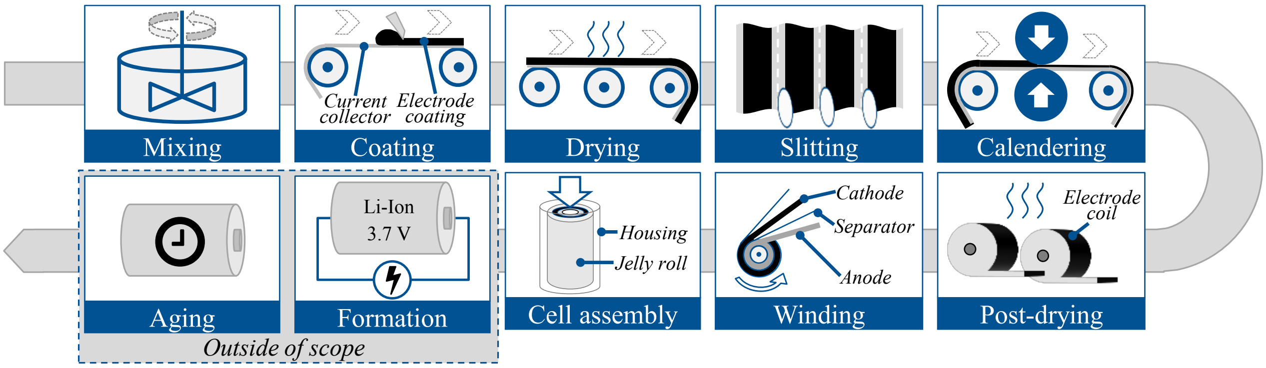

Figure 3: Process chain and individual process steps used as a basis for the simulation model

4.2 Results & Discussion

Figure 4 shows the average storage times of the products in the specific buffers along the cathode manufacturing process chain for the two scenarios.

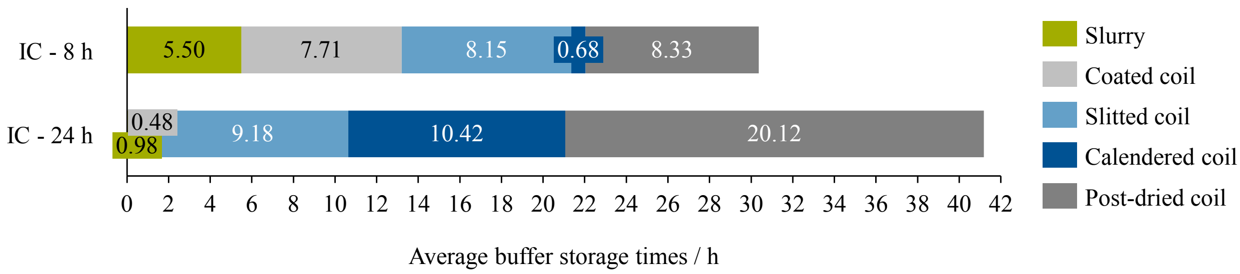

Figure 4: Average buffer storage times of the individual cathode components along the electrode process chain for the two simulation scenarios with 8 hours and 24 hours of inventory coverage (IC)

Noticeably, the variation of buffer sizes leads to a shift in the storage durations with different effects on the individual buffers. Whereas for the IC of 8 hours, rather long slurry and coated coil storage times can be detected, these durations are considerably shorter for the IC variant of 24 hours. Also, significant differences between the two scenarios can be seen for the calendered and post-dried coil storage times. These occurring imbalances can be explained by the output-based dimensioning of the buffers, leading to material quantities that correspond to the coating throughput and, hence, differ from other process steps. This consequently causes blocked machines and full buffers at certain points of the process chain. Therefore, an individual dimensioning of specific buffers in combination with machine-based adaptions would enable a more efficient buffering and material flow. This would also allow the adaptation toward material-specific aspects, considering moisture sensitivities and storage durations. These numbers demonstrate that changing the buffer size can significantly impact the production system, necessitating the adaption of production parameters along the entire process chain. Hence, it is evident that finding an appropriate production layout is a complex interaction between many parameters, suggesting to proceed iteratively.

The results also indicate that larger buffer sizes can positively influence the process efficiencies shown in Figure 5 for the two scenarios. These numbers suggest that increased buffer capacity can contribute to improved operational efficiency, as it allows for smoother material flow and reduces the likelihood of equipment downtime due to material shortages or blocked conditions. The rather low numbers for the slitting process can be attributed to the high scrap rate and relatively low availability factor assumed for this process step. For efficient production and material flow, it should be ensured that the machines are available for processing while not standing idle for longer periods. Here, available capacity in the subsequent buffer is essential to avoid blocked machines in the upstream process step. A potential approach for controlling the material flow and buffer functionality could be to adjust the coating performance, as the line balancing is carried out based on the coating process. Alternatively, adding extra machines at bottleneck positions could help to optimize the material flow efficiency. However, additional equipment entails increased investment costs and requires additional production space, also impacting OPEX.

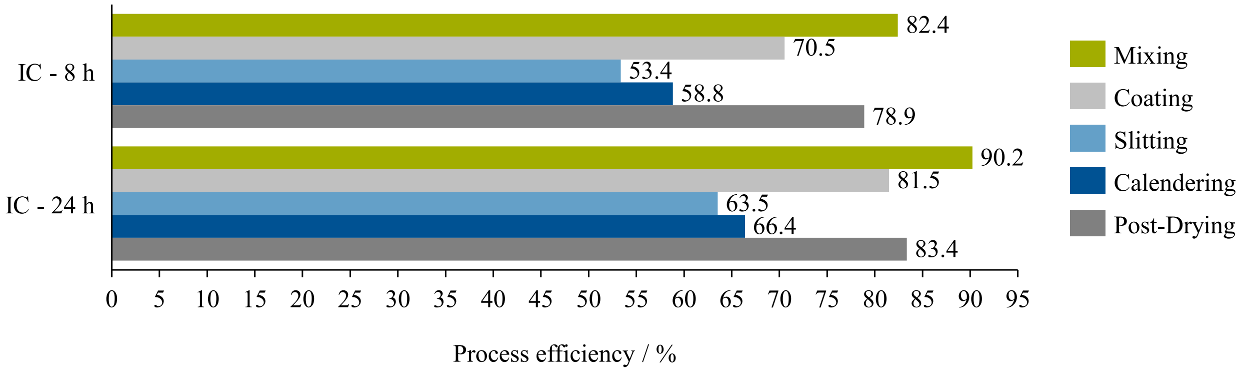

Figure 5: Process efficiencies of the cathode production line for the two simulation scenarios with 8 hours and 24 hours of inventory coverage (IC)

Furthermore, it should be noted that the model is generally very susceptible to changes in input parameters, particularly concerning the number and availability of the machines. Altering the number of parallel machines can significantly impact the calculated buffer storage times and subsequent material flow. More machines can reduce the material storage times but increase the risk of machine downtimes in case of buffer shortages. Therefore, when using the model, it is crucial to carefully assess and validate any modifications made to the machine and production layout, as they can have substantial consequences on the overall material flow and efficiency of the production system. Hence, the model is particularly effective when examining specific scenarios in real production systems, thereby supporting the decision-making process.

5. Conclusion & Outlook

The trend towards Ni-rich cathode active materials in lithium-ion battery production imposes high requirements for the production atmospheres regarding H_2O and CO_2. Therefore, cost- and energy-intensive dry rooms are used to ensure the production of high-quality battery cells. As the energy consumption of these dry rooms significantly depends on the size and desired dryness level, it is vital to identify an appropriate moisture management strategy throughout production. This work presents a methodological approach to this challenge by introducing a digital twin of a large-scale lithium-ion battery cell production to evaluate the production layout regarding material- and area-specific requirements. This model serves as a basis for electrochemical investigations of the material as it enables the prediction of exposure times for the materials and intermediate products based on a defined production layout. Hence, the model supports the planning and designing process of the factory by quickly evaluating the effects of critical production-related parameters.

As a next step, the impact of buffer sizes and the overall production layout on the required dry room space can be examined in detail, allowing to determine the effects on operational costs. Thus, it is possible to optimize the dry room area by appropriately designing the production parameters. For further development of the digital factory twin, considering the transport conditions between processes and buffers would be an interesting aspect, as this impacts the exposure time and atmosphere of the material. Concerning the overall approach, it is essential to find appropriate experimental set-ups and measurement methods for evaluating the required production atmospheres for specific cathode active materials. In this respect, it is necessary to further identify and understand the atmosphere's effects on the cell quality, as some studies indicate that under certain conditions, ambient atmosphere could be sufficient for producing high-quality Ni-rich cathodes [8,30]. Furthermore, for a detailed examination of the production layout from an energy consumption and cost perspective, a dry room model should be implemented in a battery cell production cost model. This would allow for considering the whole factory, enabling to point out the impact of the dry room operation on the total energy demand and production cost.

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Appendix

Table 2: Assumed machine, process, and production parameters for the simulation (A: Anode; C: Cathode), including the related reference (expert values and assumptions without reference)

Module	# Machines	Process speed	Coil dimension / m x cm (length x width)	Splicing factor / -	Slitting factor / -	Performance / %	Yield / % [31]	Availability / %	MTTR / s	Fixed scrap rate / m	Auxiliary process time / s
C Slurry Mixing	7	5:00 h/batch	-	1	1	100	98,5	90	7200	-	6000
C Coating	2	1,3 m/s [24]	18000 x 96	3	1	100	96,5	85	7200	300	60
C Slitting	3	1 m/s [32]	5900 x 96	3	6	100	92 [24]	75	1200	-	60
C Calendering	10	1,6 m/s [24]	1898 x 16	1	2	100	99,45	70	1200	-	60
C Vacuum Drying	4	12000 m^2/shift [24]	1746 x 8	1	1	100	99,9	95	1200	-	600
A Slurry Mixing	7	5:00 h/batch	-	1	1	100	98,5	90	7200	-	6000
A Coating	2	1,3 m/s [24]	12300 x 96	3	2	100	96,5	85	7200	300	60
A Calendering	4	1,6 m/s [24]	3933 x 48	1	1	100	99,45	70	1200	-	60
A Slitting	6	1 m/s [32]	3796 x 48	2	6	100	92 [24]	75	1200	-	60
A Vacuum Drying	3	20000 m^2/shift [24]	1887 x 8	1	1	100	99,9	95	1200	-	600
Winding	20	1,1 m/s [33]	3.3 x 8	-	-	100	95	85	180	20 [23]	1 [33]
Cell Assembly	13	36 cells/min [24]	-	-	-	100	98	85	180	-	

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Biography

Maximilian Lechner graduated in mechanical engineering at the Technical University of Munich, focusing on manufacturing engineering and the production of lithium-ion cells. Currently, he works as a research associate at the Institute for Machine Tools and Industrial Management (*iwb*) at the Technical University of Munich.

Paul Mothwurf studies mechanical engineering and management at the Technical University of Munich. Currently, he is writing his master's thesis on the challenges of the production of Nickel-rich lithium-ion battery cells.

Lasse Nohe graduated in mechanical engineering and management at the Technical University of Munich. In his master's thesis, he focused on developing an agile digital twin within the early factory design phase for the production of lithium-ion battery cells. Currently, he works as a cell cost analyst at the lithium-ion battery cell manufacturer *Northvolt*.

Rüdiger Daub has been head of the Chair of Production Technology and Energy Storage Systems at *iwb* at the Technical University of Munich and the Fraunhofer Institute for Foundry, Composites, and Processing Technology IGCV since 2021. Previously, Prof. Dr.-Ing. Rüdiger Daub has held several positions at the *BMW Group*, most recently as head of technology development and prototype construction for lithium-ion cells.