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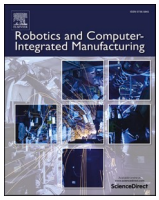

Modeling flexible configuration of cell finishing for future battery production research

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ABSTRACT

Today, the increasing demand for battery cells requires efficient large-scale production. At the same time, cell design continues to improve regarding various performance metrics causing product feature changes, which in turn affect the process chain, equipment and process parameter design in production. In cell finishing – the final cell production section – both external cell features, related to the system components, and internal cell features, related to process protocol, are directly affected. However, the interrelations between the core domains – product, process, parameters and equipment – are hardly assessed in the current cell finishing planning and thus no systematic approach to configuration design has been established. This paper focuses on this research need and presents an approach through configuration modeling based on Modularization and Knowledge-Based Design and uses real data from factory planning. From the analyzed raw data, a structured database of product, process, parameters, equipment and their interrelations are derived. For this modeling approach, the paper first explains the conceptual framework. Then, it introduces domains and sub-domains of the database and their formalization for modeling. Subsequently, the architecture of a Two-Stage Configuration Model is explained for flexible configurations (first stage) and virtual modeling (second stage). Finally, the modeling approach is implemented for a real case of prismatic cell finishing. It demonstrates how various configurations can be systematically generated and visualized based on design requirements to advance design optimizations in cell finishing for research purposes and industrial application.

1. Introduction

Current market trends indicate a significant increase in demand for large capacity battery cells, primarily driven by the global increase in electric vehicle adoption [1]. To meet this growing demand, it is essential to develop large-scale production facilities for battery cells [2]. Achieving this scale of production requires technologies that are both reliable and stable, operating at a Technology Readiness Level (TRL) above 6. This level of maturity is required for GWh-scale battery production and ensures that applied technologies can effectively support large-scale operations . [3] At such a scale, the general requirements for large-scale production include considerations of production time and cost. In battery cell production, further consideration for a degree of flexibility and adaptability is also necessary to accommodate variations in production processes and materials [4,5].

Previous research on modular products, reconfigurable processes, and agile manufacturing has evolved to meet the challenges of rapidly changing market demands. The principles modularity, reconfigurability and agility are equally applicable to large-scale battery cell manufacturing. The rapid pace of product development in this area is driven by innovations in fast-charging cell configurations, material recyclability, and increased cell capacity. These advancements require a flexible and adaptable manufacturing system to keep pace with changing market demands . [6,7]

Battery cell manufacturing is divided into three main sections: electrode manufacturing, cell assembly, and cell finishing. This paper focuses on the cell finishing, which faces several unique challenges:

1. *Equipment Specifications*: Cell finishing involves cell activation, requiring appropriate equipment specifications to handle cell-specific designs. Both mechanical and electro-chemical effects affect cell quality at this stage, so parameter specifications can vary and affect the applicability of the production equipment [8].
2. *Variability in Process Duration*: The overall production time in cell finishing varies depending on the cell design and the duration of the core process steps of formation and aging which can range from days

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to weeks per cell [7]. The exact process duration must be determined individually through experimental testing [9].
3. *Energy Intensity*: Cell finishing is the most energy-intensive section in cell production. Implementing energy saving concepts will significantly reduce operating costs [10].
4. *Protocol Definition*: The cell finishing protocol defines the cell-specific finishing process and specifies parameters for each cell finishing step. For safety and quality reasons, for example to avoid defects and production rejects, only validated protocols for comparable cell sizes and chemicals are applicable [8,11].

The challenges described above offer optimization potential. The solutions to these challenges would contribute significantly to reducing costs and saving resources since material and production cost at cell level account for 70 % of the total cost of the traction battery which in turn accounts for 40 % of the total cost of the electric vehicle [12]. When combined for large-scale cell finishing, optimizations achieved by individual improvement relating to the challenges above will be highly effective due to synergies and scaling effects [13,14]. In this context, a holistic assessment of efficiency requires a fundamental understanding of the interrelation between various factors associated with cell characteristics, process and measurement technology and innovation regarding cell finishing [14].

As the cell designs develop dynamically along the Technology Readiness Level (TRL), future cell designs will differ from those currently in production [5,15]. Constant adaptation of the production design is necessary [5,9]. Our previous studies described the importance of a thorough understanding of the interrelation between battery cell design and cell finishing system and the necessity to manage the increasing complexity due to data extension [5,9]. Using the example of prismatic cell design, data collection and processing were implemented through a service-oriented approach and demonstrated on selected features [9]. To effectively address the challenges of cell finishing in such a dynamic development environment, a comprehensive understanding needs further to comprise interrelations (*IM*) between product design (*PM*), cell finishing process (*CM*), equipment (*EM*) and process parameters (*AM*) [7,11]. Considering the interrelations mentioned, the objective of this paper is to propose a configuration modeling approach to identify optimal cell finishing configurations, with a focus on cost and time related requirements. In this modeling, reconfigurability, reusability, and scalability are considered essential characteristics. To achieve this objective, the research employs two established methodological approaches: *Modularization* and *Knowledge-Based Design*. These approaches facilitate the creation of flexible and adaptable production systems, enabling efficient responses to the dynamic demands of large-scale production.

Modularity provides a foundation for flexible design in product and production development. Employing modular design in production further enables the creation of a virtual production design that can be implemented in the real world. Configuration systems, which are typically knowledge-based, assist in decomposing complex systems into simpler components, making them applicable to manufacturing. These systems are based on data collection and validation, including design and plant experience . [16]

The following section consists of a brief review of the state of the art in Section 2, to introduce the current works predominantly focused on cell finishing process development and laboratory-scale parameter optimization. It is followed by the introduction of the conceptual framework for configuration modeling, with the applied methodological approaches and the Two-Stage Configuration Model detailed in Section 3. Then, a real-case implementation is presented in Section 4 to identify and visualize appropriate configurations for a prismatic production line. This section demonstrates design possibilities and presents a template for large-scale cell finishing production design.

2. State of the art

In this section, we present an overview of the current research in the domain of large-scale cell finishing production. The state-of-the-art of cell finishing processes is explained concisely. The research in cell finishing is categorized into two principal areas based on production scaling.

One research area focuses on the parameter optimization of the core process cell formation, providing important insights into the design of formation parameters to improve cell quality. This research predominantly involves low-capacity cells and single-layer pouch cells, with notable contributions from Stock et al. (2022) on parameter optimization, Schomberg et al. (2024) on various formation strategies and lab-based validation, Cui et al. (2024) on data-driven quality analysis, and Zou et al. (2024) on battery quality classification and lifetime prediction [17–19].

The other research area focuses on the development of cell finishing processes. Key contributions include Kampker et al. (2023) on cell type-dependent process routes, Plumeyer et al. (2023) on process innovations and the relocation of electrolyte filling to cell finishing, and Robben et al. (2024) on the potential of integrating measurement technology, such as Electrochemical Impedance Spectroscopy (EIS), in cell finishing [7,8,11]. To provide an overview of the cell finishing, a general description of the process chain is illustrated in Fig. 1 and explained below.

The first process step Electrolyte Filling could be integrated into the cell finishing for large-format cells, typically prismatic cells, allowing for more efficient and precise control of process parameters. After the *1st Electrolyte Filling*, a second electrolyte filling may be required. *Pre-Treatment* varies among thermal, electrical, and mechanical methods depending on the cell format. Soaking involves storing the cell at elevated temperatures (30–60 °C) in temperature-controlled rooms to reduce the electrolyte's contact angle and improve the uniform wetting of the electrodes. This step takes between 12 and 24 h. Pre-charging, an electrical treatment, performs the initial charging before formation. The cell is charged to a 20–30 % state of charge (SoC) with a low C-rate to the highest level of gas development. *Formation* based on specific protocols, activates the cell by charging and discharging, ensuring a stable Solid Electrolyte Interphase (SEI), which is crucial for the cell's lifespan, capacity, and safety. Formation protocols vary depending on the application and include parameters such as current rate (0.05C to 0.5C), number of charge cycles (1–5 cycles), temperature (20–50 °C), duration (up to 24 h), and voltage limits. During formation, electrochemical reactions within the battery cell cause gas development in the battery housing. For small-format cells, *Degassing* may be optional. For large-format cells, e.g. prismatic cells, this step is necessary to minimize safety risks due to undesirable cell expansion. The *2nd Electrolyte Filling* is an optional step to compensate for electrolyte loss and optimize cell performance features. Sealing the cell ensures a hermetic seal to prevent electrolyte leakage, typically achieved through laser welding. During the *Aging*, cells are stored for up to three weeks. This process is divided into high-temperature aging (HT aging) at 30–50 °C and room-temperature aging (RT aging) at 20–25 °C. The purpose of aging is to ensure the long-term functionality and safety of the cell while stabilizing chemical processes. During storage, the open circuit voltage (OCV) is

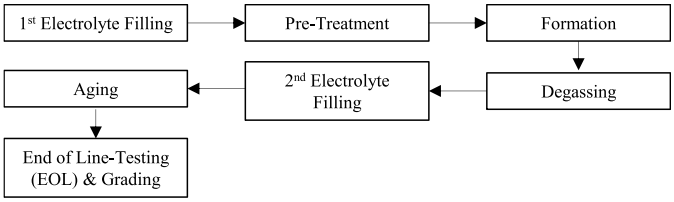


Fig. 1. General description of cell finishing.

monitored to determine the self-discharge rate for cell quality assessment. The last steps *End of Line-Testing (EOL) & Grading* involve verifying cell quality through electrical, mechanical, and optical tests. Following *EOL* tests, cells are automatically categorized into quality classes based on the test results. At the end of the cell finishing processes, the graded cells are packaged into safety transport boxes . [7,8,22]

As illustrated in Fig. 2, related topics of current cell finishing research are highlighted. In comparison, current research in process development contributed partially to production flexibility [7,8,11]. They provided the foundation for a basic understanding of cell finishing processes. Indeed, cell finishing production needs to consider equipment and product as well to create flexible configurations for large-scale cell finishing production. The first research in this direction was by Kokozinski et al. (2024) on the influences of flexible product design for production, providing initial insights into the external product features and production equipment. However, none of the previous research could cover all design aspects of product, process, parameters and equipment of a manufacturing system. Furthermore, there is no research on the configuration or reconfigurability of cell finishing production.

3. Configuration design

The preceding section reviewed current research and highlighted research gaps in addressing flexible production configuration. This section introduces the proposed approach to configuration modeling through *Modularization* and *Knowledge-Based Design*. The methodology and conceptual framework are explained, followed by the Two-Stage Configuration Model (TCM).

3.1. Methodology and conceptual framework

The conceptual framework is developed on two core methodological approaches *Modularization* and *Knowledge-Based Design*. Both terms and their application in the context of this paper are explained below.

Utilizing *Modularization*, data collected during the current research project of plant planning can be uniformly formalized, decomposed into independent elements, and combined into modules defined by validated boundary properties. Therefore, it helps to maintain flexibility despite the complexity of data in the production planning. It further facilitates a flexible configuration in virtual environment that matches the real-world production [20,21]. In summary, the modularization in production design applies to the following requirements and assumptions of our configuration modeling for cell finishing:

- Modularity: Implementing a manufacturing system based on *Modularization* allows for a "high degree of independence among individual elements" in different modules and ensures interchangeability between modules [20,21].
- Factory Layout: Typically, "linear and fixed", facilitating streamlined processes . [20]
- Reconfigurability: Modular manufacturing facilitates the rapid and straightforward restructuring of production lines, enabling the efficient manufacturing of multiple products. Modules can be rearranged or replaced [20].
- Adaptability: Elements can be "added, deleted, or modified to adjust production functionality and capacity" [22,23].
- Simple Interfaces: Modules are grouped into blocks with simple interfaces, aiding in the identification and integration of the appropriate module [22].
- Virtual Factory Concept: *Modularization* is "closely tied to the concept of a virtual factory, where a physical factory is precisely modeled". Design, simulation, and process control are executed virtually, comparable to a "digital twin" . [20]

Knowledge-Based Design (KBD), and in this application, *Knowledge-Based Configuration (KBC)*, is established for configuration systems of complex products and services. It is originally defined as "a collection of Schema Representation Language (SRL) that represents physical and abstract system entities" [23,24]. The so-called schemas work with constraints or concept definitions to create the model. *KBC* is widely used in product development and utilizes Artificial Intelligence techniques to simulate possibilities with suitable and sufficiently linked information (Knowledge-Based Simulation System). This places certain requirements on the interfaces and the data system in terms of redundancy and consistency within the systems. This approach requires:

- Preparation and structuring of basic elements and alternatives in production since complex systems consist of simple elements.
- The elements must be formalized, and their relations must be described [24].

Both approaches are embedded into the conceptual framework, illustrated in Fig. 3. It consists of two sections. The first section (Section I) uses the *KBC* by building a system of defined units, constraints and relations. *Modularization* helps to develop the configuration elements to achieve structured and simple design and avoid redundancy. It uses the database as the input and delivers production concepts by the configuration model. Its space of solution is limitable via the requirements input. The second section (Section II) of the framework transfers the solution as data, saved in a Design Structure Matrix (DSM), into a visual representation. This approach helps systematically address both high-level design and detailed specifications [25,26]. The visualization is achieved through graphical programming in the SIMULINK, a MATLAB-based environment. Through basic visual models representing production modules, a comparison to a real production environment can be provided for plant design cofiguration and optimization.

3.2. Data description of basic elements

The database for the configuration modeling is designed to meet the requirements of *Modularization* and *KBC* approaches and described in Section 3.1. An overview of the database design is illustrated in Fig. 4 and explained in the following.

The database is organized into two hierarchical levels. At the foundational level, the analyzed datasets are classified into six distinct domains. Within each domain, the fundamental data elements are stored as

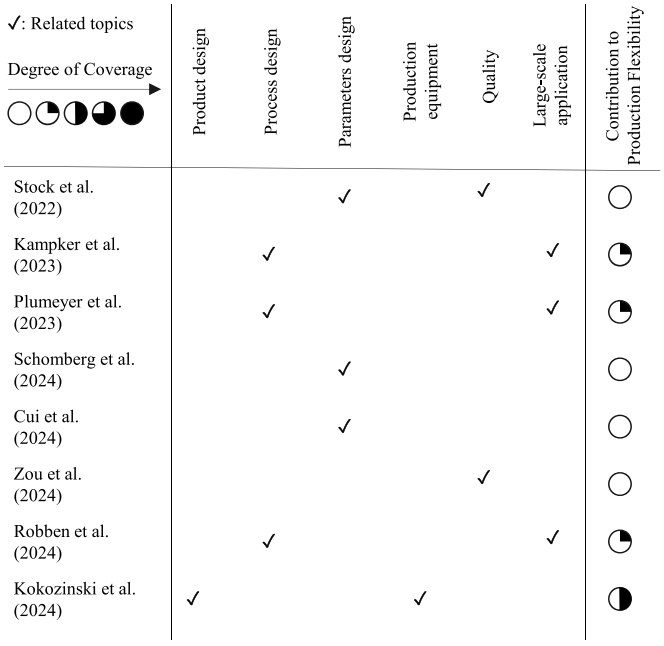


Fig. 2. Overview of current cell finishing research.

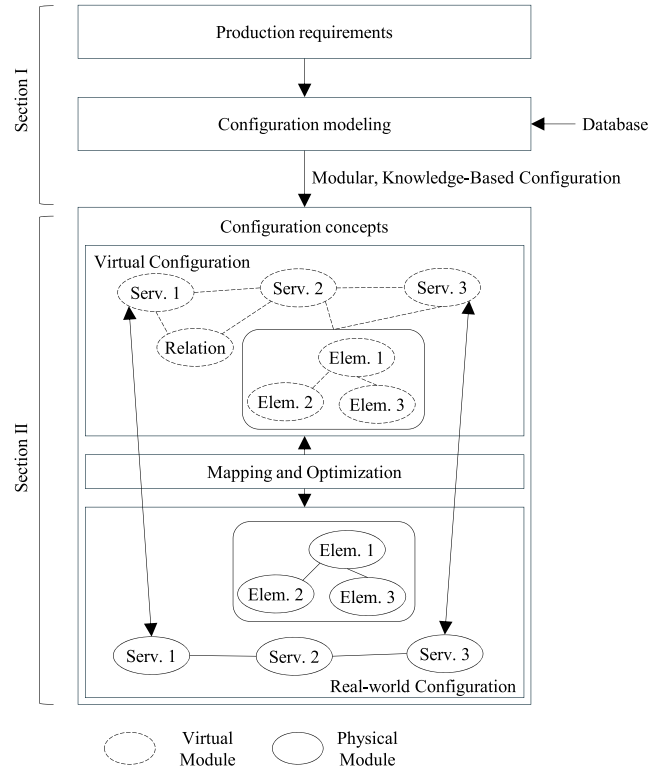


Fig. 3. Conceptual framework.

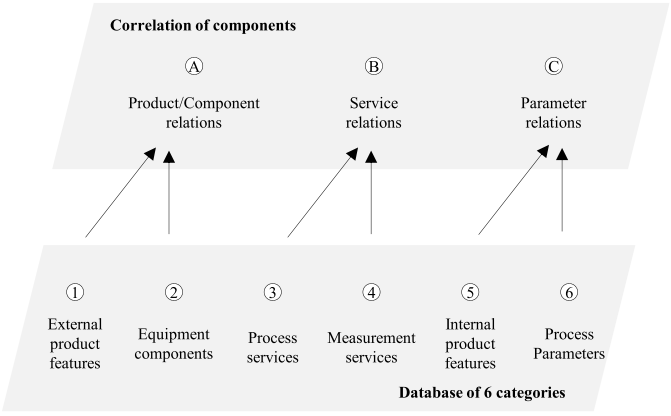


Fig. 4. Database.

the basic domain elements, designed to meet the requirements of *Modularization* as simple and independent. Correlation matrices are employed to assign relations between these elements. Beyond the six data domains, additional relations are organized in Domain A, B and C. For instance, correlations can be established between external product features and equipment components to define physical interfaces in production.

The correlation data constitute the second level of the database, which is essential for production configuration, encompassing aspects of product, equipment, process and parameters. The boundary conditions derived from these relations are crucial for the functionality of the configuration model in delivering solutions. It is well understood that *KBC* applications rely on data collection and context-dependent analysis. Nevertheless, both the data and the relation descriptions can be formalized according to *KBC*. In the following, the data composition is explained, and data formalization is introduced.

Based on identified correlations of the external product features, and the service-orientated architecture approach, product features are structured in external and internal features and processes are divided into production processes and measurement processes that are subdivided into sub-services [5,9]. An overview of the data composition is illustrated in Fig. 5.

The external features include, for example, the design of the terminal, the tab configuration and the dimensions of the battery cell. They are formally described as $P_{i,ex}=\{P_{1,ex}, P_{2,ex}, \ldots, P_{n,ex}\}$.

The battery cells pass through various stages in production, which comprise at least one production process. Each production process provides at least one production service, which includes sub-services. These can be used for active process execution or supportive process execution. The service modules can be represented formally by $S_{i,p}=\{S_{1,p}, S_{2,p}, \ldots, S_{n,p}\}$.

During the implementation of the services, the battery cells are in direct contact with certain components of equipment. For example, charging and discharging the cells is a core service in the formation process, where the tabs of the cell and the charging channels of the formation chamber are the physical interfaces. To perform this active process step, the formation tray supports as a fixture and can exert controlled pressure on the cell, whereas the tray's inner layers and cell housings form another physical interface. The equipment components are formalized as $C_i=\{C_1, C_2, \ldots, C_n\}$ and the Product/Component interface via their relations as $P_iC_j=\{P_1C_1, P_2C_2, \ldots, P_mC_n\}$.

Distinguishing between production processes and measurement processes is essential because cell production is not complete until the production processes are finished, while measurement processes can be optionally integrated or repeated. Therefore, fixed processes and flexible measurement process modules need to be clearly organized to expand the configuration options. In some cases, integrated inline measurement is necessary as it serves as quality check due to safety-related factors. In these cases, a 100 % inspection needs to be added to the production process. In certain instances, optional quality inspections could take place at a different time or process stage to collect targeted testing data for a testing concept that can be evaluated in- or off-line. Examples of safety relevant measurement include the leakage test after the sealing to eliminate the risk of the electrolyte leakage from the cell housing, and thermal measurement of the cell during formation and aging to prevent cells from overheating due to undetected damage. Optionally placeable measurements include, for example, electrical measurements that can record the cell capacity and electrical resistance at different times to track the electrical properties of the cell during production, and ultrasonic measurements that can be implemented for extended testing purposes. The measurement process modules are formalized as $S_{j,m}=\{S_{1,m}, S_{2,m}, \ldots, S_{n,m}\}$.

External product features $P_{i,ex}=\{P_{1,ex}, P_{2,ex},\ldots,P_{n,ex}\}$	**Equipment components** $C_i=\{C_1, C_2,\ldots,C_n\}$	**Process services** $S_{i,p}=\{S_{1,p}, S_{2,p},\ldots,S_{n,p}\}$
$P_{1,ex}$ $P_{2,ex}$ … $P_{n,ex}$	C_1 C_2 … C_n	$S_{1,p}$ $S_{2,p}$ … $S_{n,p}$
Measurement services $S_{j,m}=\{S_{1,m}, S_{2,m},\ldots,S_{n,m}\}$	**Internal product features** $P_{i,in}=\{P_{1,in}, P_{2,in},\ldots,P_{n,in}\}$	**Process parameters** $A_i=\{A_1, A_2,\ldots,A_n\}$
$S_{1,m}$ $S_{2,m}$ … $S_{n,m}$	$P_{1,in}$ $P_{2,in}$ … $P_{n,in}$	A_1 A_2 … A_n
Product/Component relations $P_iC_j=\{P_1C_1, P_2C_2,\ldots, P_mC_n\}$	**Service relations** $S_{i,p}S_{j,m}=\{S_{1,p}S_{1,m}, S_{2,p}S_{2,m},\ldots, S_{m,m}S_{n,n}\}$	**Parameter relations** $F_{i,x,celltyp}=\{F_{1,x,\ celltyp}, F_{2,x,\ celltyp}, \ldots, F_{n,x,celltyp}\}$
P_1C_1 P_2C_2 … P_mC_n	$S_{1,p}S_{1,m}$ $S_{2,p}S_{2,m}$ … $S_{m,m}S_{n,n}$	$F_{1,p,\ celltype}$ $F_{1,m,\ celltype}$ $F_{2,p,\ celltype}$ $F_{2,m,\ celltype}$ … … $F_{n,p\ celltype}$ $F_{n,m\ celltype}$

Fig. 5. Data domains.

Service relations describe whether the process module is fixed or interchangeable, whether it is necessary or optional. It also contains the time and process allocation, for example that the insulation test is to be conducted after electrolyte filling and before formation. The service relations are summarized as $S_{i,p}S_{j,m}=\{S_{1,p}S_{1,m}, S_{2,p}S_{2,m}, \ldots, S_{m,m}S_{n,n}\}$ and can be illustrated as in Fig. 6.

Process parameters refer to physical, electrical or thermal parameters that are kept within a tolerance range to provide the cells with optimum conditions at each production step. They are defined based on simulations, series tests or pilot production. The parameters of the production process and measurement process modules are collected and assigned to the corresponding module components. The defined process parameters are used in production steps to influence the electrochemical development inside the cell. In measurement steps, they are used to interpret the reproduced signals for the changes within the cell or its quality status. Unlike the interfaces between the external features of the cell and the components of the system, the correlation between the cell's internal features $P_{i,in}=\{P_{1,in}, P_{2,in}, \ldots, P_{n,in}\}$ e.g., the active materials for electrodes or electrolyte composition, and the process parameters $A_i=\{A_1, A_2, \ldots, A_n\}$ e.g., charging rate, temperature and pressure setting, are not physically visible. However, clear identification of suitable process parameters for cells with different internal features directly affect the cell electrical quality. Cell-specific finishing protocols contain specified parameters for each process module so that a database of cells with different internal features can be established.

Restrictive conditions derived from production requirements are needed to achieve required configuration results and define possible configuration designs. The production requirements are formalized as $L_i=\{L_1, L_2, \ldots, L_n\}$. The input of the production requirements depends on each production planning team and is responsible for the configuration output.

3.3. Modeling procedure

A Two-Stage Configuration Model (TCM) is designed to involve an initial stage to define the basic modules based on production requirements with a first output of selected configurable modules. The output data are represented in a Design Structure Matrix (DSM), a square matrix used to define sequential relations of applicable modules. The second stage of the model aims to visualize configuration possibilities based on module relations via a SIMULINK model which represents real-world plant planning. The final output consists of selected modules in the streamline of the production, marked in DSM and presented in a virtual model. The configuration design is dependent on product design (*PM*), cell finishing process (*CM*), equipment (*EM*), process parameters (*AM*) and their interrelations (*IM*) represented by the database: $S = f(PM, CM, EM, AM, IM)$. The final configuration designs can be described as S', a subset of the total solution set S by fulfilling all conditions in production requirements L and all module relations M, i.e., $S' = \{x \in X \mid \forall l \in L \,\&\, m \in M\}$. The modeling procedure including the data input and model output is illustrated in Fig. 7. Based on calculations regarding process time, energy and maintenance effort, optimizations can be derived.

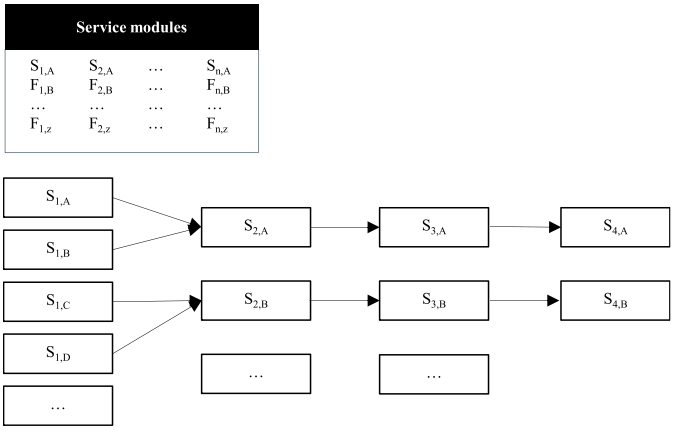


Fig. 6. Extract of service module relations.

4. Example of implementation

This section uses the example of the prismatic cell finishing planning for the research factory (FFB Fab) at *Fraunhofer Research Institution for Battery Cell Production (FFB)* in Münster, Germany. By implementing the modeling approach described in Section 3, different configurations can be derived for the cell finishing design.

The configuration modeling is suitable for the use case with the main objective to develop large-format cell finishing configurations to be applied for the factory FFB Fab in Münster, Germany. As part of the research project, the prismatic cell finishing production needs to fulfill the large-scale production requirements and provide a flexibility corridor to accommodate both internal and external product modifications. Process and testing functions should be extendable to incorporate innovative measurement or production technologies in the future. The current cell design variants (medium and large) and the layout planning for the prismatic line are illustrated in Fig. 8.

The cell finishing plant is part of the FFB Fab. There are certain production requirements defined for the design of the cell finishing: The prismatic cell finishing line receives the entry cells transferred from the prismatic cell assembly. For prismatic cell manufacturing, cell assembly delivers so-called „dry cells", which are mechanically assembled and not filled with electrolyte. The production speed in cell finishing is input-dependent with the requirement to pick up cells from cell assembly without delay. Due to the output rate of prismatic cell assembly defined at 1 cell per minute (cpm), the same production speed is defined for prismatic cell finishing. Further, cell finishing is designed to cover two cell designs (medium and large) which will not be produced

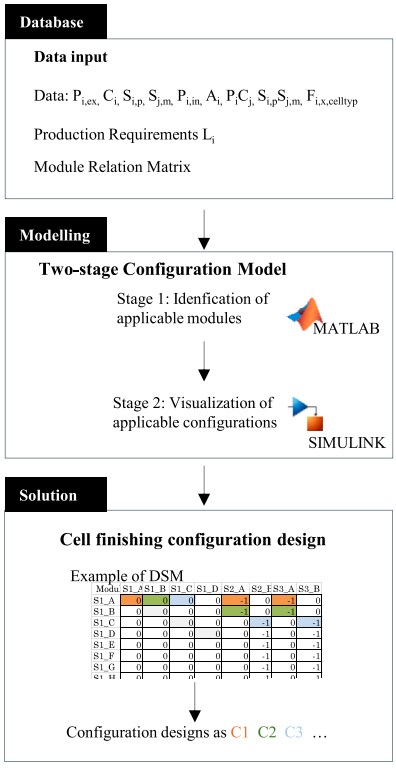


Fig. 7. Modeling procedure.

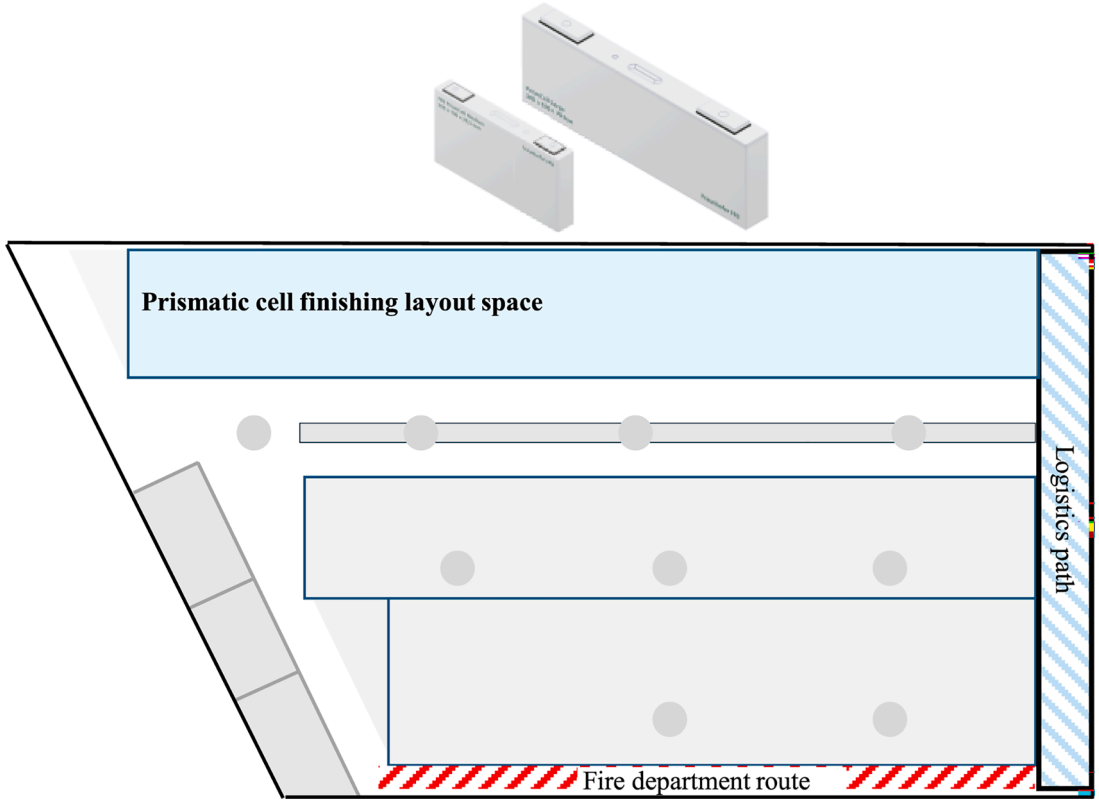


Fig. 8. Current FFB cell design and layout.

simultaneously on the same line. Based on the throughput of 480 cells per day in prismatic cell assembly, the same throughput per day is defined for cell finishing. Cell finishing is defined to operate continuously with fully automated processes, resulting in a maximum of 2400 cells per week. The cell finishing protocol based on the basic process design, outlined in Fig. 9, defines the process time and process parameter for the two cell designs (medium and large). During the planning and the modeling, these requirements serve as the fundamental design framework which is also representative of industrial cell finishing.

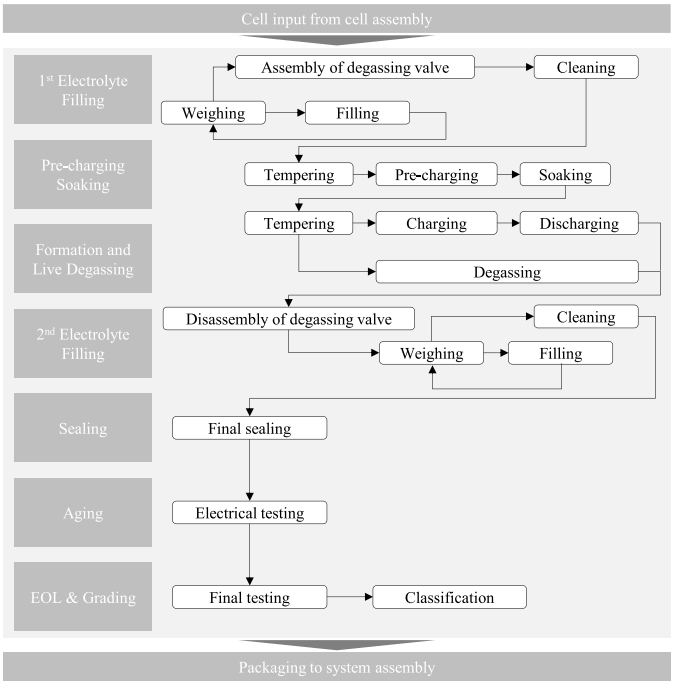


Fig. 9. Basic process design for prismatic cell finishing.

Database: During the cell finishing planning, we have collected and analyzed data on product features, equipment components and tested protocols for Prototype A to establish suitable parameters and process procedure of the prismatic cell finishing [5,9,27]. The process description in Fig. 9 is established for the prismatic cell finishing line as a basic reference [27]. It allows for configuration design to accommodate the process into an overall plant concept together with identified measurement technologies. Various inline integrations are possible, in terms of time sequences, before, during and after the manufacturing process steps. However, implementing numerous measurement processes would also increase production time. It is essential to carefully assess the impact of measurement strategies on production rate and cell quality. When integrating measurement technologies and designing the measurement parameters, the measurement processes used for quality assurance must be integrated as effectively as possible into necessary production steps developed for the specific cell design. The selection of measurement technologies and inline integration should be targeted to reduce rejects, detect defects at an early stage, and improve cell quality.

Modeling Stage 1: Based on the data composition described in Fig. 5, the configuration modeling is initiated via MATLAB scripts. Since the configurations need to match the basic process, the current cell design and layout space, the configuration possibilities are limited to $L=\{L_1, L_2, L_3\}=\{Basic\ process, Cell\ design, Layout\ space\}$. The results are shown in a DSM, in which 22 modules are identified as applicable. If no other boundary conditions are added, the module relations would lead to final configuration concepts.

Modeling Stage 2: Through the DSM and the module relations which define their connection in a streamline process, the modules are assembled to fulfill the requirements L. The final configuration designs can be described as follows (see. Fig. 10).

The modules consist of independent elements as subsystems. To provide an overview of its composition, the modules *S1_A, S1_B* and *S1_C* and their subsystems are presented in Fig. 11, with dotted outline for localization in clean and dry room, and white elements for intralogistics transition. The extract shows the module architecture. By the example of *S1_A*, it is described as: *S1_A={S1_A_1.1, S1_A_1.2, S1_A_1.3, S1_A_1.4, S1_A_1.5, S1_A_1.6, S1_A_1.7, S1_A_1.8, S1_A_1.9}={Loading cells from assembly to C&D room, Loading cells from assembly to warehouse, Weighing before filling, Filling via filling lance, Insulation test, Assembly of temporary closing pin, Cleaning the filling area, Weighing after filling, Loading on formation tray}*.

The same architecture is applied to all modules. In total, 42 independent sub-systems are applicable to designing 22 modules for the outcome of 8 configurations. To visualize the configurations, a visual representation is created in SIMULINK. The simulation environment is designed with the same principle of *Modularization* and uses the correlation matrix for defining rules and constraints. That means, for each modular element and module, as illustrated in Fig. 11, there is a digital representation in the virtual world. For example, Fig. 12 shows the virtual model of the presented module *S1_A*.

To present the possible configuration solutions based on $L=\{L_1, L_2, L_3\}$, the 8 options are illustrated below (see Figs. 13 - 20). They offer model-based support by designing cell finishing production or further optimization regarding detailed assessment of technology innovation and maturity, energy efficiency, flexibility degree of both external interfaces and system parameters [14].

Configuration 1

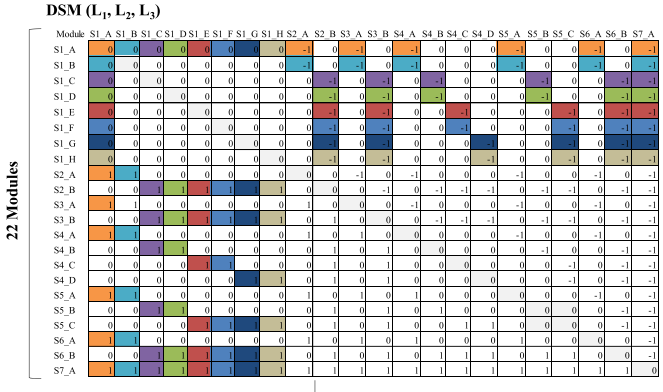
C1={S1_A, S2_A, S3_A, S4_A, S5_A, S6_A, S7_A}.

Configuration 2

C2={S1_B, S2_A, S3_A, S4_A, S5_A, S6_A, S7_A}.

Configuration 3

C3={S1_C, S2_B, S3_B, S4_B, S5_B, S6_B, S7_A}.



Configurations

C1	S1_A	S2_A	S3_A	S4_A	S5_A	S6_A	S7_A
C2	S1_B	S2_A	S3_A	S4_A	S5_A	S6_A	S7_A
C3	S1_C	S2_B	S3_B	S4_B	S5_B	S6_B	S7_A
C4	S1_D	S2_B	S3_B	S4_B	S5_B	S6_B	S7_A
C5	S1_E	S2_B	S3_B	S4_C	S5_C	S6_B	S7_A
C6	S1_F	S2_B	S3_B	S4_C	S5_C	S6_B	S7_A
C7	S1_G	S2_B	S3_B	S4_D	S5_C	S6_B	S7_A
C8	S1_H	S2_B	S3_B	S4_D	S5_C	S6_B	S7_A

Fig. 10. Identification of applicable modules and configurations.

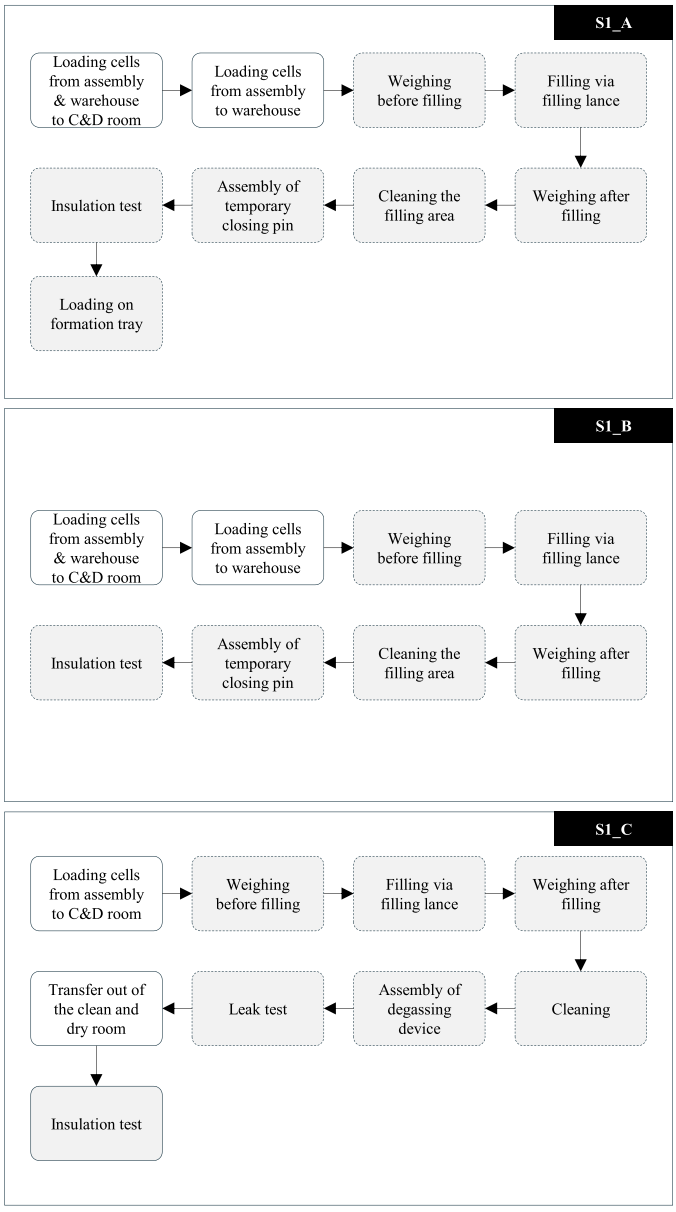


Fig. 11. Extract of modules.

Configuration 4

C4={S1_D, S2_B, S3_B, S4_B, S5_B, S6_B, S7_A}.

Configuration 5

C5={S1_E, S2_B, S3_B, S4_C, S5_C, S6_B, S7_A}.

Configuration 6

C6={S1_F, S2_B, S3_B, S4_C, S5_C, S6_B, S7_A}.

Configuration 7

C7={S1_G, S2_B, S3_B, S4_D, S5_C, S6_B, S7_A}.

Configuration 8

C8={S1_H, S2_B, S3_B, S4_D, S5_C, S6_B, S7_A}.

These configurations can be used in the planning for the future factory FFB Fab. At the current stage of cell finishing planning, the configuration model supports evaluating design configurations based on

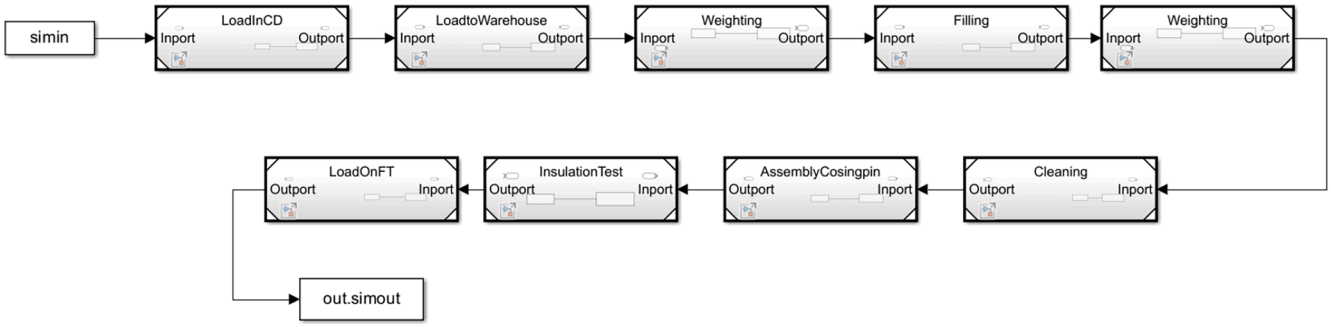


Fig. 12. Simulink module *S1_A*.

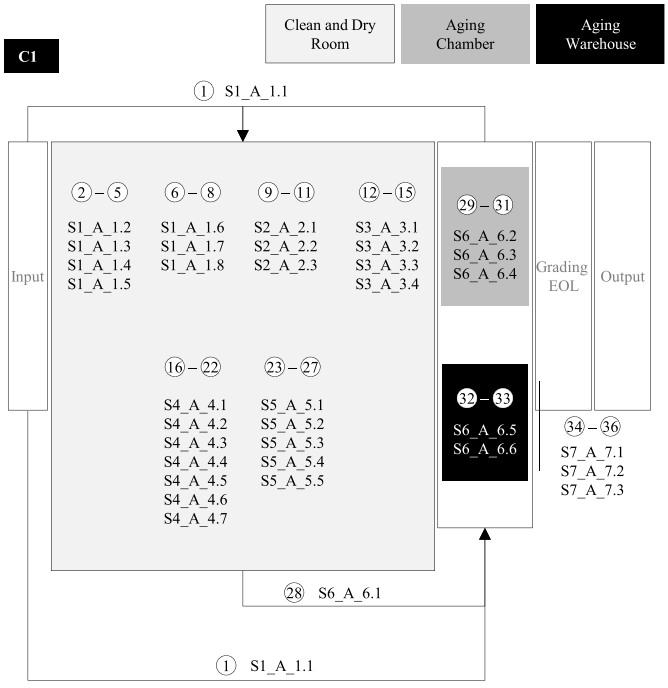


Fig. 13. Configuration 1 (C1).

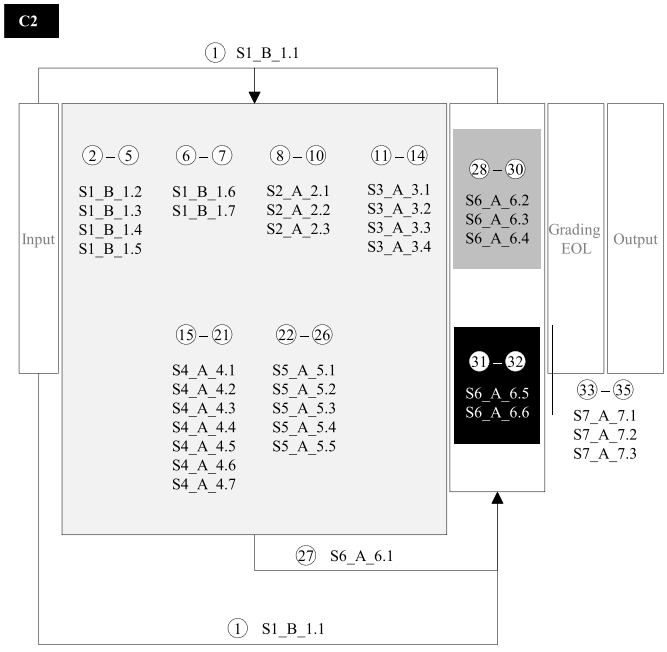


Fig. 14. Configuration 2 (C2).

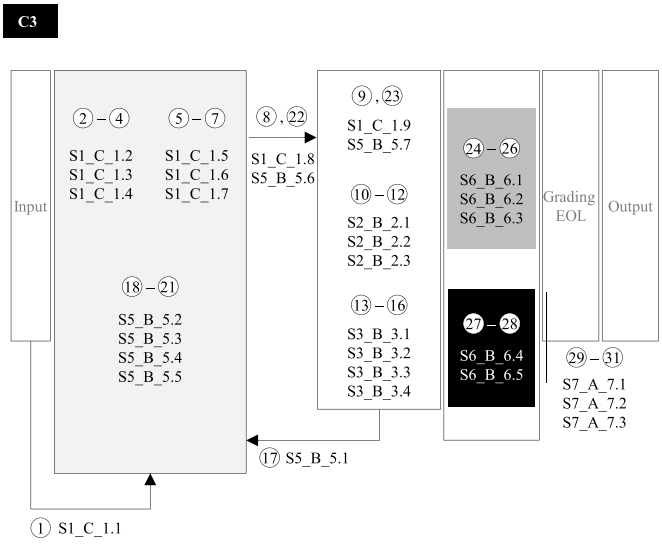


Fig. 15. Configuration 3 (C3).

additional constraints, such as energy-saving potential and the capacity for function extension within the fixed layout. Due to fixed requirements regarding defined throughput and production speed, cell finishing configuration concepts can be compared based on estimated space consumption in the three main production areas which cause different intensity on energy consumption during operation. Two critical factors in optimizing energy efficiency are the operation of a clean and dry room (Area A) and energy consumption during formation and aging processes (Area B) [10]. The duration of formation and aging is determined by the cell-specific finishing protocol and the advanced equipment which is assumed to incorporate regeneration and recuperation functions. Consequently, the utilization of the clean and dry room (Area A) becomes a crucial factor for comparison. Despite the high energy consumption due to process steps within the clean and dry room, the number of infeed and outfeed processes can substantially impact energy costs and needs to be considered as well. In area C, normal production conditions are defined, which are comparatively less energy-consuming. The energy required to maintain each production area increases with the number of processes conducted within it, leading to significant differences among the 8 configurations (see Fig. 21). For instance, Configuration 1 (*C1*), as shown in Fig. 13, requires 26 production services within the clean and dry room (Area A), whereas Configuration 8 (*C8*), illustrated in Fig. 20, requires only 9. As illustrated

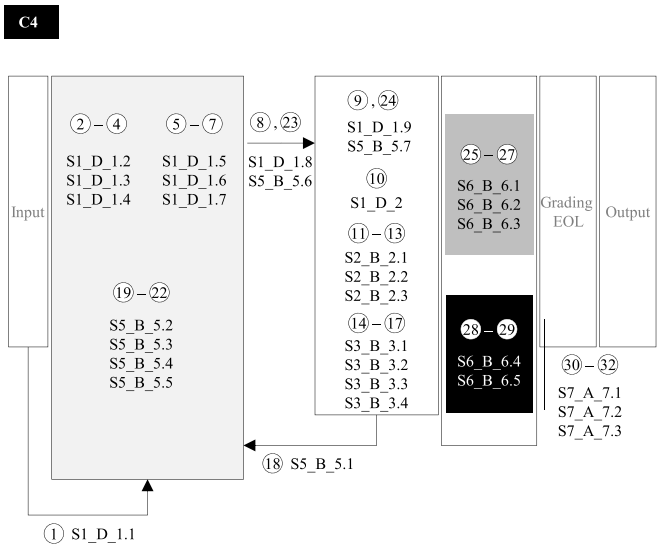


Fig. 16. Configuration 4 (C4).

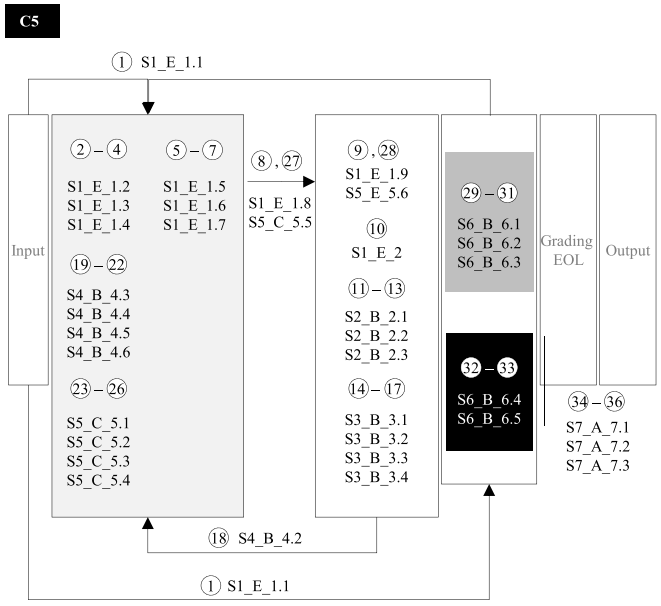


Fig. 17. Configuration 5 (C5).

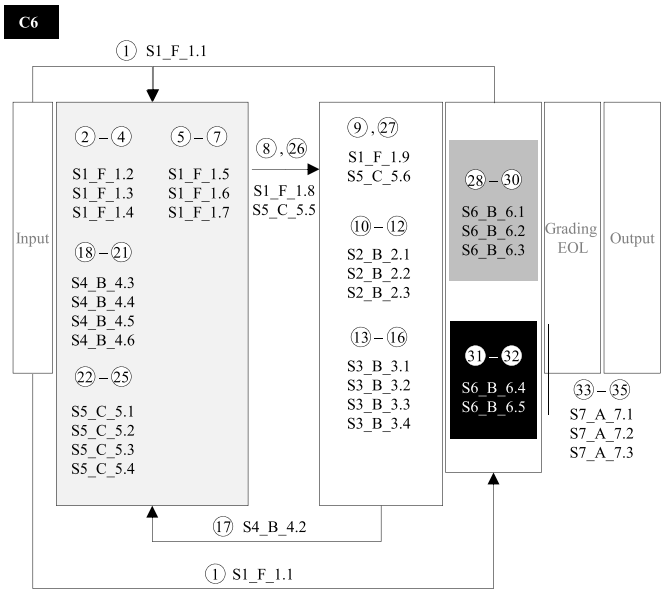


Fig. 18. Configuration 6 (C6).

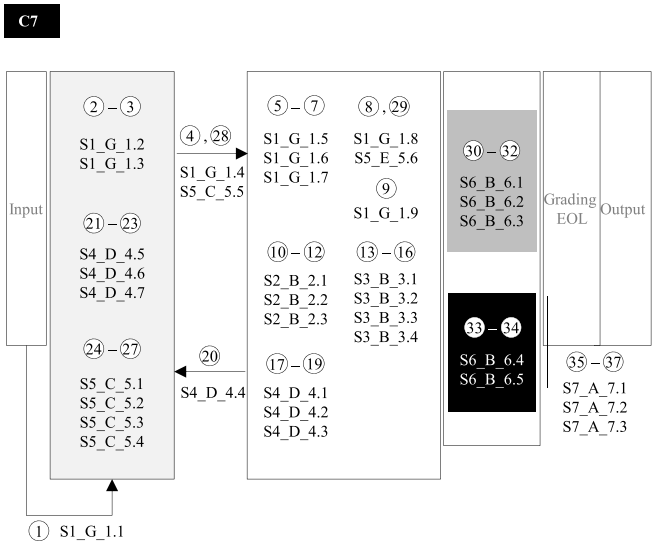


Fig. 19. Configuration 7 (C7).

in Fig. 22, a direct comparison of the two configurations reveals that *C1* necessitates a substantially higher energy input per batch to execute the processes within and the conditioning of the clean and dry room as compared to *C8*.

Based on the pre-conditioning for the plant design and prototype testing, the applied cell finishing protocol is defined. The energy consumption caused by cell finishing (as part of cell manufacturing) is therefore considered similar in a relative comparison of the 8 configurations. This is also evident when comparing the *C1* and the *C8*. Quantitative differences can arise by testing the specific equipment on the same cell finishing protocol. The energy required for formation and aging is considered the greatest among the total consumption in cell finishing production. Therefore, further quantitative comparisons between equipment, to be expected in further plant development, can be measured regarding these two crucial processes. Concurrently, higher energy consumption can incur substantial operating costs, a factor that can be remarkable depending on the plant location. Using the example of *C1* and *C8*, the potential savings in energy consumption, attributable to the reduced number of processes in Area A of *C8*, offer significant cost advantages over *C1*, by reducing operation costs of production. As the acquisition costs of equipment must also be taken into account, they will be calculated at the time of equipment procurement.

The evaluation criteria for energy, space of each production area and costs by a defined throughput and protocol are decisive for the selection of production systems for large-scale cell finishing. In addition, further aspects covering a range of battery cell and process design flexibility are relevant for the evaluation of the use case. Due to rapidly developing battery cell designs and the necessary process adaptations, these flexibility aspects may also become the focus of industrial applications.

Therefore, the ability to extend functions within the fixed cell finishing layout is crucial for the planning of a research battery cell factory, which aims to test emerging technologies on-site in the future. As new technologies emerge, new modules can be easily integrated into a virtual system. However, modifications to a real factory are naturally constrained. To ensure a certain degree of flexibility in this production line, the feasibility of extensions based on existing configuration design must

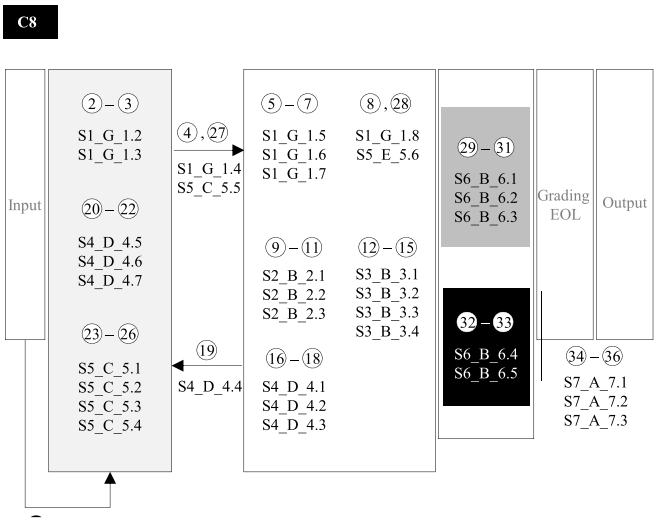


Fig. 20. Configuration 8 (C8).

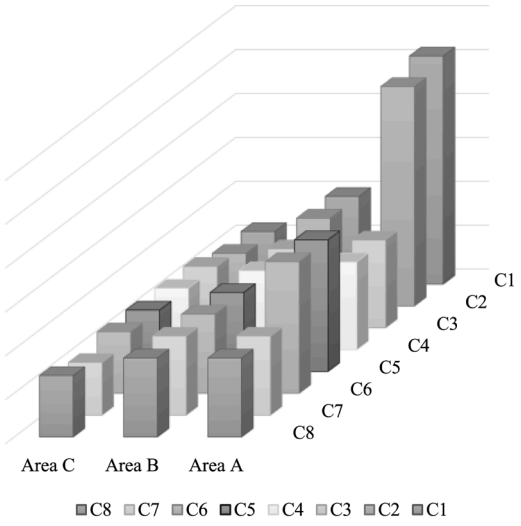


Fig. 21. Estimated space of production area A, B and C by configuration.

be evaluated. This feasibility is primarily influenced by the remaining space in the planned layout area and the need to avoid interventions in critical areas, such as clean and dry rooms, to limit expenses. Due to space and connection considerations, configurations *C3, C4, C5, C6, C7*, and *C8* offer greater flexibility advantages over *C1* and *C2*. Among them, *C7* and *C8* provide the highest flexibility, although the process stability outside the clean and dry room and the technological maturity must also be considered.

Between the flexibility degree and the level of technological maturity, a design decision can be made to ensure adequate process stability for large-scale production. The current approach of the research team involves designing both "Baseline" and "Superline" concepts to streamline basic requirements, while positioning special technologies in stand-alone locations that are integrable into the main production line (Baseline) by stacker crane transport [27]. This approach facilitates the integration and comparison of new technologies with basic technology. Flexible configuration modeling serves as a foundation for virtual simulations, allowing for thorough testing of production concepts to address potential issues for operation during the concept design phase. Together with the continuing prototype testing of the large-format prismatic cell at the Battery Testing Center of the *Chair of Production*

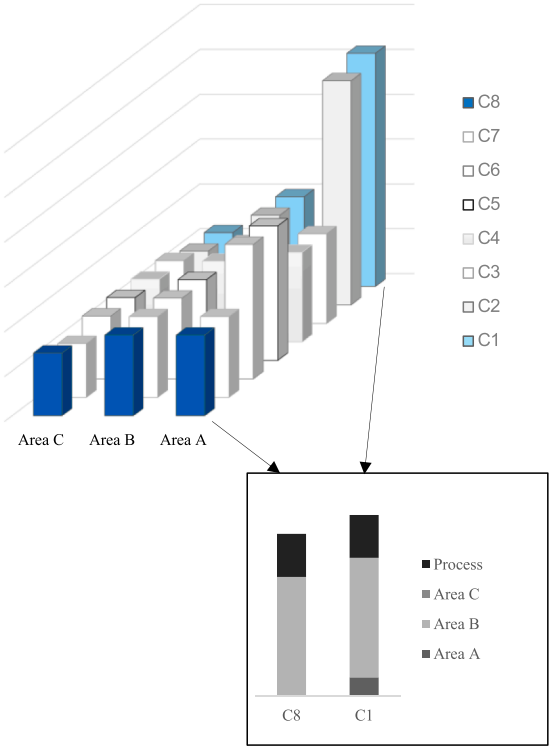


Fig. 22. Comparison of energy consumption due to area conditioning and process energy consumption.

Engineering of E-Mobility Components of RWTH Aachen (*PEM*), module and parameter relations applied will be further extended for the configuration model.

5. Conclusion and outlook

Due to the complexity of cell finishing production that involves both mechanical and electrochemical influences between the battery cell, cell finishing process and the production system, we briefly outlined the major challenges regarding *Equipment Specifications, Variability in Process Duration, Energy Intensity* and *Protocol Definition*. To consider this complexity and identify possible configuration solutions, we presented a knowledge-based and modular configuration approach with considerations of product (*PM*), process (*CM*), parameters (*AM*), equipment (*EM*) and their interrelations (*IM*), resulting in design solutions $S = f(PM, CM, EM, AM, IM)$. The use of *Modularization* and *KBD* enables the reduction of complexity of cell finishing into smaller components that can be flexibly reconfigured based on the constraints. To achieve reliable configuration modeling, a database of six data domains and module relations were analyzed and structured. Via a Two-Stage Configuration Model (TCM), production requirements L and module relations M are considered to limit the solution space $S^{'} = \{x \in X \mid \forall\, l \in L \,\&\, m \in M\}$.

The presented modeling approach contributes to the cell finishing design in early phases of planning to evaluate different design concepts and to avoid missing aspects in the complex relations between product, process, parameters and equipment that may affect the cell finishing production in the long term. It can also be applied for optimizing existing cell finishing plants to identify the potential of reconfiguration and assess the expense of modifications. Additionally, virtual modeling can be used to visualize the configuration concepts that match the real-world cell finishing design.

Our design approach for flexible cell finishing configuration is implemented in the use case of the current research project FoFeBat2. For this project, our proposed configuration approach led to 8 possible

plant configurations consisting of 22 modules and 42 independent elements. The 8 configurations are applicable for large-scale production planning and fulfill the requirements of *Basic process, Cell design* and *Layout space* (defined for the prismatic cell finishing) at the FFB Fab in Münster, Germany. Differences in available technology for the production services result in different plant configurations. To identify the optimal configuration for this use case, more constraints are needed based on design decisions or priorities which could include energy efficiency, space efficiency and process efficiency. To facilitate quantitative comparison on those aspects, the current database will be supplemented with detailed information on equipment acquisition and consumption in the next stage. In comparison to cylindrical and pouch cells, the prismatic cell production design is more demanding due to the greater complexity of production, such as live degassing during formation and intermediate filling. Therefore, by adapting the reference process description (see Fig. 9), updating the basic database and data correlation (see Fig. 4), the presented approach is adaptable for production of cylindrical and pouch cell formats.

For future research, the database for the configuration modeling will be extended with continuing updates of applicable technology and cell design features for large-scale production. Especially, current data on cell-specific process parameters can be extended based on our near-series prototype testing, to provide parameterized protocols for various cell designs leading to a holistic configuration for cell finishing planning, thus laying the foundation for adaptive cell finishing with Artificial Intelligence. Beyond the application in the research project, it has the potential to be applied for industrial use cases to reduce uncertainties and complexity of interrelations of cell design, process, parameters and equipment in cell finishing, and to maximize plant flexibility while increasing the overall design efficiency.

CRediT authorship contribution statement

Sicong Deng: Conceptualization, Data curation, Formal analysis, Investigation, Methodology, Project administration, Resources, Software, Validation, Visualization, Writing – original draft, Writing – review & editing. **Jonas Wieskamp:** Investigation. **Henrik Born:** Supervision. **Heiner Hans Heimes:** Funding acquisition. **Achim Kampker:** Funding acquisition, Supervision.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Supplementary materials

Supplementary material associated with this article can be found, in the online version, at doi:10.1016/j.rcim.2025.103119.

Data availability

The data that has been used is confidential.

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