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# Potentials and Implementation Strategies For Flexible Battery Cell Production

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**Abstract**

The effects of a fossil fuel-based economy are becoming increasingly apparent. The storage and use of renewable energy sources are a key strategy to reduce overall greenhouse gas emissions. In this context, the demand for batteries as a suitable medium for energy storage is increasing rapidly. Lithium-ion batteries pioneered in consumer electronics are nowadays used in ever more applications, with the e-mobility sector being one of the most prominent. From a production perspective, the process chain for manufacturing of such lithium-ion batteries can be divided into three main sections: electrode production, cell assembly and cell finishing. However, actual implementation of the process chain differs substantially, depending on the selected cell format (pouch, cylindric, prismatic) and design, manifesting in cell-specific processes (e.g. stacking vs. winding), supplementary and/or omitted process steps and manufacturing technologies (e.g. pouch foil heat sealing vs. hard case laser welding). Currently there is no strictly preferred cell format, as each format has its advantages and disadvantages, depending on its intended application and system integration. Production of different battery cell types thus is spread across various international – mostly Asian – manufacturers, most of which have large scale mass production lines dedicated to a single specific format. Only a few manufacturers have a portfolio of formats (e.g. round and prismatic) in large quantities. Against this background, the following paper provides an overview of the product variety of lithium-ion batteries available on the market, following up with a discussion of potentials and implementation strategies for flexible battery cell production. First, applications and business areas for lithium-ion batteries are analysed and general flexibility areas regarding the battery cell design are derived. Subsequently, the impacts of the different flexibility areas on the production processes are analysed. In a final step, different implementation strategies and approaches for increased flexibility in battery cell production are elaborated.

**Keywords:** Battery Cell Production; Production Planning; Flexibility; Implementation Strategies

## 1. Introduction

The storage and use of renewable energy sources are a key factor in becoming independent of fossil fuels and minimizing greenhouse gas emissions. As a result, the demand for batteries as a suitable medium for energy storage is increasing rapidly. [1] Lithium-ion batteries (LIB) originated in consumer electronics are now being used in more and more domains, currently mostly prominently in various e-mobility applications. Main reasons for their market dominance are their long cycle life, high power density and continuously improving energy density. Considering the constant demand for energy sources for transport and environmental concerns about conventional fuels, the demand for lithium-ion batteries has been rising steadily for years. [2] For this reason, and due to the rapid increase in electrification of the mobility sector, global demand for LIBs is expected to exceed 4 TWh in 2030. [3] New battery concepts and new battery

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chemistries are being researched and developed to support this transformation. However, at the same time the battery industry is facing short product life cycles, a growing number of variants and a wide range of applications leading to a high level of technological and market uncertainty. This poses major challenges not only for the product development of new battery cells but also for their production and manufacturing process. [4] .

Current battery cell production plants are designed to manufacture predefined battery cells with a high level of automation, at highest quality, and with minimal deviations in end product characteristics. Production lines focused on high production volumes are trimmed for maximum efficiency and yield, thus relying on a highly streamlined process flow. Once ramped up, these factories are kept at their optimal operating point with the clear objective on standardizing production runs. Once operations and production are fine-tuned, leading battery cell manufacturers try to maintain the optimum operating window for as long as possible with as few changes necessary and deviations as possible. Form this point of view, flexible production of varying customer-specific battery variants in quickly adjustable quantities poses a major challenge for existing factories. Therefore, this paper assesses prerequisites, potentials and implications of product and process flexibility in the battery cell production context and elaborates on different strategies for practical implementation.

## 2. Fundamentals

### 2.1 Flexibility in manufacturing systems

Great volatility in customer behaviour and supply chains as well as a fast-moving market pose a great challenge for companies manufacturing lithium-ion batteries. They are forced to adapt to frequent and rapid changes induced by the changing market environment and growing regulatory pressure. [5]

Organizational forms of manufacturing companies can be divided into different categories as shown in Figure 1. Depending on whether the focus is on a high product variety or on a high production volume, the orientation and production system setup leans either towards flexibility or productivity. While most high-volume production lines are typically designed for dedicated cell formats and variants in order to achieve the required outputs at minimum possible cost, pilot-scale production lines primarily serve R&D activities. In this production environment material testing, process validation and integration as well as scale-up of new technologies and innovations are prioritized.

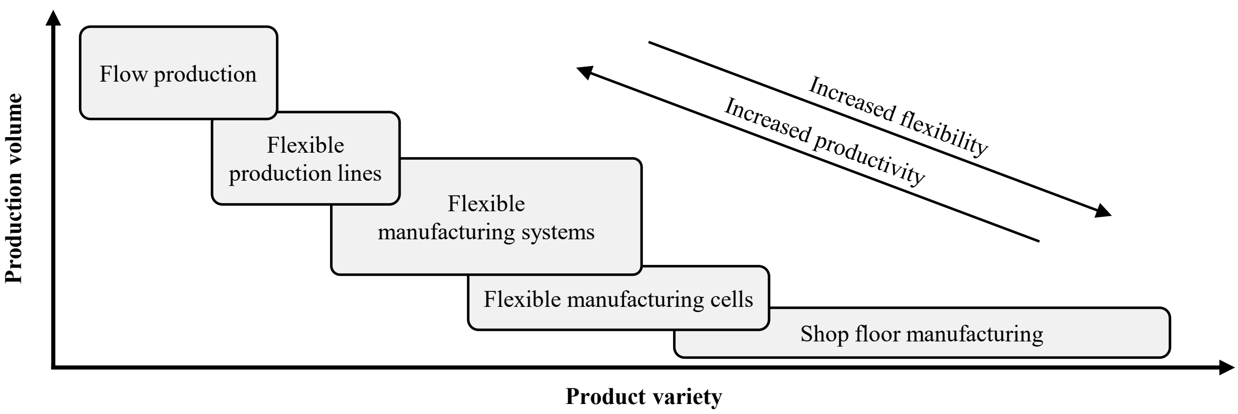


Figure 1: Overview of organizational forms in manufacturing [6]

Product diversity at the cell level is closely related to the diversity of battery-powered applications in the industrial landscape. However, market segments such as electromobility, aerospace, wearables, etc. have inherently different requirements for batteries in terms of performance, lifetime and basic product characteristics such as size and format. In order to redesign a production system into one that bridges the gap between mass production and customised manufacturing, relevant flexibility potentials of the production system need to be well distinguished and addressed accordingly. [4] Following classifications for flexibility in manufacturing are commonly distinguished in scientific literature: [5–9]

- Machine flexibility: Ability to execute the changes needed to produce a given mix of products
- Material flexibility: Ability to handle variations in composition and dimension of parts
- Operation flexibility: Ability to change the sequence of operations and the performing machines
- Volume flexibility: Ability to manufacture economically with different production quantities
- Expansion flexibility: Ability to expand the production apparatus component by component
- Routing flexibility: Ability to change the routes of the parts in case of machine failure
- Process flexibility: Ability produce different parts with different requirements in different ways
- Product flexibility: Ability to perform a changeover to the production of new products

## 2.2 Current status in lithium-ion battery cell production

Currently, the lithium-ion battery is the most advanced energy storage technology and a key component, specifically in the field of electric mobility. Further developments are intended to improve the performance, cost-effectiveness, environmental friendliness and safety of existing LIB systems. In addition to cell technology, research is also being conducted in the fields of materials technology, process technology and battery cell production.

### 2.2.1 Structure of lithium-ion batteries

The basic structure of a lithium-ion battery cell consists of two electrodes (anode and cathode) composed of active materials coated on current collectors, a separator, liquid electrolyte and a housing. [10]

The predominant active material for anodes is graphite, because of its low price and reasonable storage capacity of lithium-ions. Silicon is also considered as an upcoming anode material. In theory it has a much larger capacity to store lithium so that the specific electric capacity of the cell can be significantly increased. [11] The cathode can consist of a variety of different materials. Currently most prevalent cathode chemistries are lithium-nickel-manganese-cobalt-oxides (NMC) followed by lithium-iron-phosphate (LFP) and lithium-nickel-cobalt-aluminium-oxides (NCA). [12] The active materials for the electrodes are applied in the form of a slurry on thin metal foils (current collectors). The active material is dried into a porous structure and becomes completely immersed in liquid electrolyte. The electrolyte ensures ionic charge exchange between the electrodes and is composed of conducting salts dissolved in high-purity organic and anhydrous solvents. The microporous separator serves as an insulator between the electrodes, preventing short circuits and allowing the ionic current to pass through at the same time. [13,10]

Depending on the cell design (pouch, prismatic or cylindrical), the anodes and cathodes are stacked or wound into an electrode-separator composite (ESC), with the separator alternating between the anode and cathode. The separate layers of the current collectors are welded together and contacted by tabs. Afterwards the cell stack or roll is placed and enclosed in an impermeable housing (either hardcase or pouch foil). [13]

### 2.2.2 Process chain in battery cell production

Generally, the production processes for lithium-ion batteries can be divided into three main sections: Electrode production, cell assembly and cell finalization (Figure 2). [14]

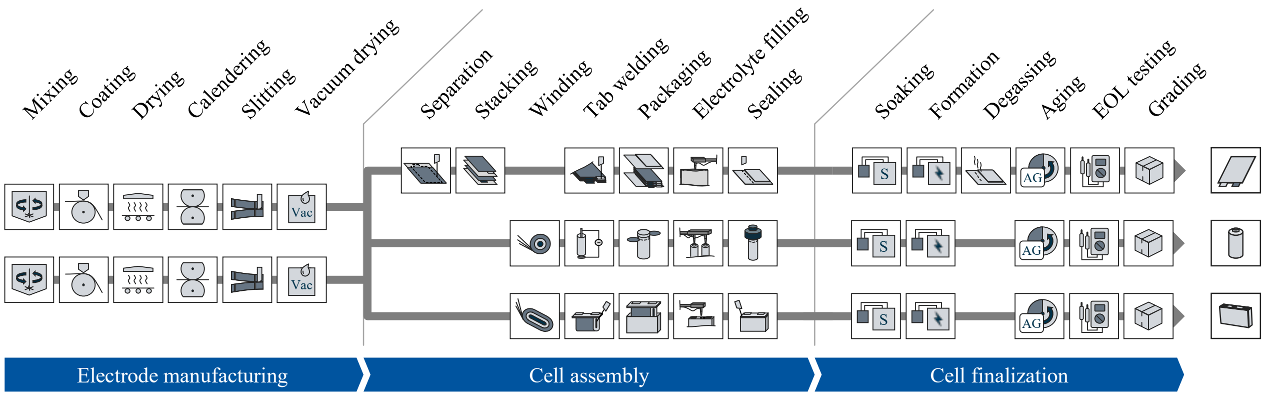


Figure 2: Generic process chain in battery cell production (top-down: pouch, cylindric, prismatic)

Electrode production begins with weighing and mixing the active materials with various additives and solvents to form a slurry. The slurry is then coated onto a thin metal foil in a roll-to-roll process and immediately dried in a convection oven, where the solvent is removed again. The electrodes are then calendered, i.e. pressed for a specific porosity. Depending on the dimensions of the battery cell, the large mother coils are cut into smaller daughter coils. Finally, vacuum drying takes place to remove any residual moisture from the material. Typically, a battery cell production has two separate production lines for anode and cathode to avoid material contamination.

In cell assembly, the electrodes are assembled into a cell. This involves alternately assembling the anode, separator and cathode to form the electrode-separator composite. After that, current collectors are welded and contacted with tabs to form the battery cell's terminals. The electrode-separator-composite is then placed in the housing, which is filled with electrolyte and ultimately sealed hermetically. However, actual implementation of the process chain differs substantially, depending on the selected cell format (pouch, cylindric, prismatic) and design, manifesting in cell-specific processes (e.g. stacking vs. winding), supplementary and/or omitted process steps and manufacturing technologies (e.g. pouch foil heat sealing vs hard case laser welding). Thus, cell-specific assembly lines are mainly being considered for high-volume production in the Gigafactory scale.

In cell finalization, the assembled battery cell is electrochemically activated for the first time. At the beginning, wetting takes place, where it is ensured that the electrolyte is completely and sufficiently distributed within the entire cell. Only then can formation continue, in which the battery cell is charged and discharged under controlled conditions to form the solid electrolyte interface (SEI). During this process, gases are released which have to be extracted from within the cell. Afterwards, the battery cell undergoes an aging phase, where it is monitored and controlled for any anomalies such as for example low capacity retention and performance losses. At the end, the EOL testing and grading of the battery cell is performed based on the performance parameters recorded throughout the cell finalization. [15,14,13]

## 3. Approach

The main objective of implementation strategies of different flexibility types in production is a demand-driven manufacturing of product variants, while ensuring an optimal capacity utilization with high economic efficiency at the same time. Therefore, a high reactivity and adaptability of the production is required in order to realize an adjustment to different changes in the market. [16] The objective of this paper is to investigate and evaluate the potential of flexibility in battery cell production to enable an increase in customer and market orientation while maintaining economic and demand-driven production of customized lithium-ion batteries. Figure 3 shows the underlying approach for this paper.

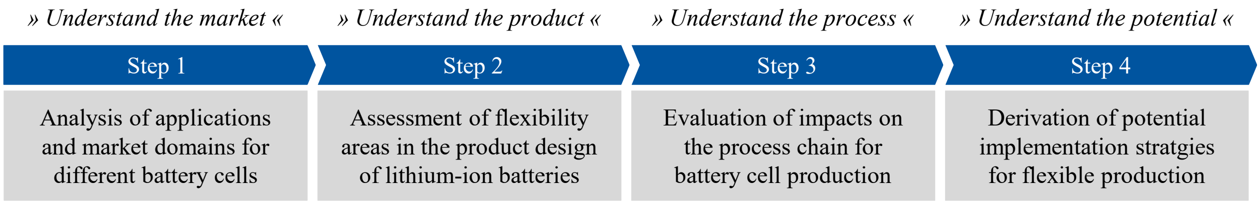


Figure 3: Approach for deriving implementation strategies for a flexible battery cell production

## 4. Results

While previous approaches [4,17,18] on agile battery cell production have focused primarily on the aspect of functional units for the process steps based on a prototype facility, the following analysis will look in particular at scaled implementation strategies aiming for flexibility in battery cell production within an industrial relevant scale.

### 4.1 Potential market demand for flexibility in battery cell production

A high number of applications and business opportunities for batteries have been established over the last three decades. Figure 4 shows the key findings of a meta-study conducted by PEM, which divides the total battery market into several core domains, outlining their battery demand, market value and anticipated development.

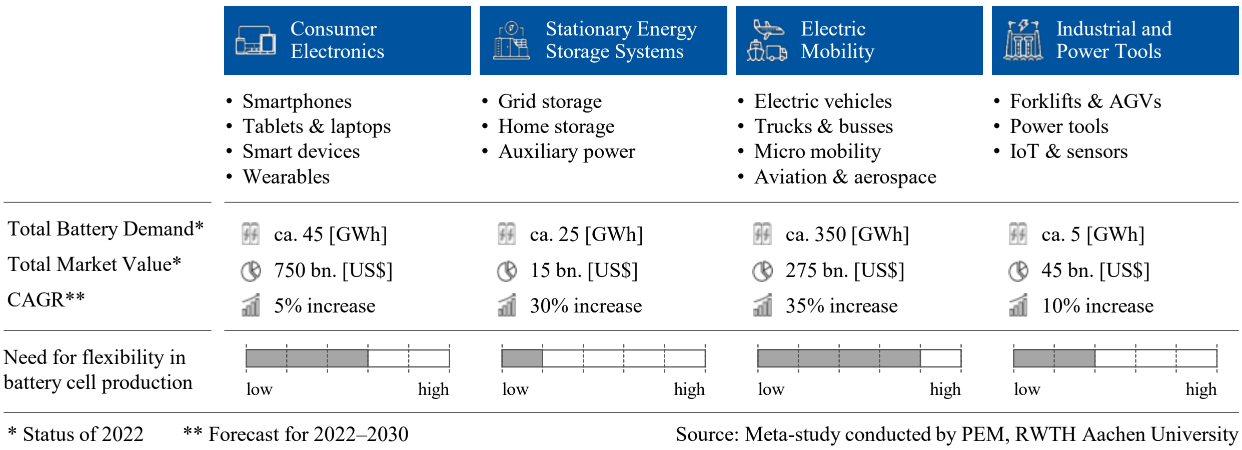


Figure 4: Market overview for established and emerging markets for lithium-ion batteries

A further breakdown of these core domains (consumer electronics, stationary storage, e-mobility, industrial and power tools) reveals several individual segments that are constantly bringing along new innovations. Due to the rapid technological development, various battery powered products such as for example wearables, smart devices and other niche gadgets can be seen adding to the market. Beyond this, a multitude of new and emerging markets are driving the battery industry. Most prominent domains cover electric transport and aviation, which include various forms of electrified transport on paved roads and in the air. Besides, stationary energy storage systems, as well as industrial and power tools for various types of industrial equipment and applications, are growing in total produced quantities. Together, these emerging markets account for a significant share of today's total battery demand, reflected in about 380 GWh of already deployed capacity in 2022.

Applications in the emerging markets (especially in the premium segments) thereby are more likely to show noticeable demand for custom battery solutions and thus flexible battery cell production. Examples include the fast-growing electric aviation market and the market for sports and hyper cars. They are characterized by constraints in space and weight as well as high performance requirements, motivating optimally integrable battery solutions

### 4.2 Flexibility potentials in the design of lithium-ion batteries

As previously outlined, the rapid development and optimization of battery cell technology in various industries is accompanied by a large number of product variants. These can differ significantly in terms of format, chemistry and other product properties depending on the market and application requirements. A stage-gate process for the generalized development of lithium-ion battery cells is shown in Figure 5.

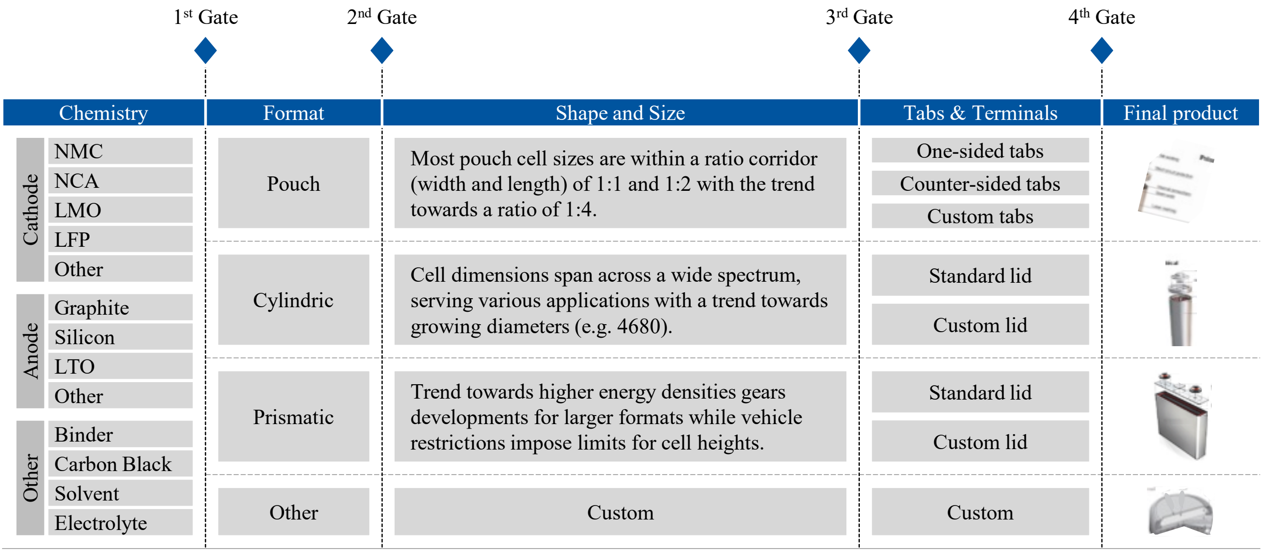


Figure 5: Stage-gate process for the development of different lithium-ion battery cells

In general, these design stages, accounting for a variety of specifications can be summarized and classified as cell chemistry, cell format, shape and size, as well as contacts, with latter referring to tabs and terminals that provide the electrical contacting at the module level. These four aspects are responsible for the majority of different cell variants observable in the grand battery landscape. With the selection of the active materials, the formation of the cell core (electrode-separator composite), and the interfaces for electrical contacts they represent clear distinguishing features of a lithium-ion battery, eventually determining final product properties and performance characteristics. For sake of completeness it should be mentioned, that there are additional cell components, that are subject to only minor changes so that they can be seen as standardized items (e.g. current collector foils, centre pins).

### 4.3 Flexibility potentials in the process chain of battery cell production

As previously described, the generic process chain for lithium-ion batteries is divided into the three main areas of electrode production, cell assembly and cell finishing, each of which applies to all common cell formats. Figure 6 highlights the process sensitivity within battery cell production regarding the different product changes for lithium-ion batteries.

In direct comparison, electrode production has the highest flexibility with regard to the individual cell formats, as they are all based on a current collector foil coated with active material. Anode and cathode production are therefore largely uniform, apart from process-related differences in coating patterns, widths and thicknesses. Different cell chemistries such as NMC, LFP or NCA can be processed with great flexibility. The effort required to adapt to new product variants is relatively low, as it mostly involves adjustments to the process parameters (e.g. mixing times and speeds) without the need for further changes to the equipment. However, changeovers may be necessary e.g. in case of the slot die for processing rheological significantly different slurry mixtures or applying particularly thin layers.

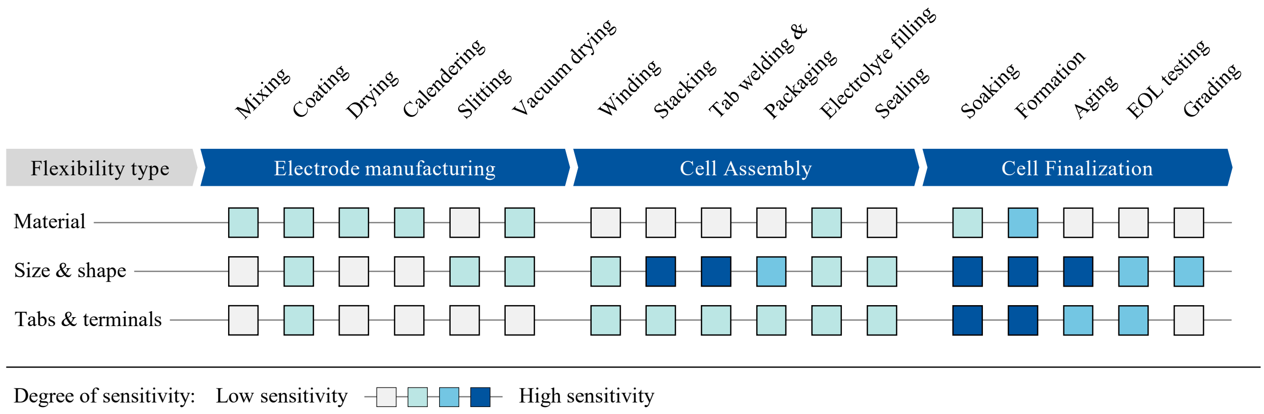


Figure 6: Process sensitivity regarding the different design aspects for lithium-ion batteries

The main implications on the process chain are particularly noticeable in cell assembly. All three cell formats are based on different assembly and production steps, which require different manufacturing technologies, handling processes and quality inspections.  As within this section of the cell production, a large number of cell-specific components is assembled, even slight product changes are reflected in severe propagation effects, extending on several downstream process steps. An illustrative example can be given by alternated tab positions for the pouch cell, where not only the cutting and notching processes require tool changes, but also, welding, sealing and the whole set of process accompanying measures such as handling, tool alignment etc. While some minor variations in cell design can be accommodated by the flexibility of current off-the-shelf equipment, limits are quickly reached due to tools, manufacturing technologies and automation specifically adjusted to the produced battery cell.

Cell finalization remains largely similar across all cell formats, whereas only the pouch cell deviates more due to the need for active degassing and subsequent resealing. The equipment used for the electrochemical activation of the battery cell is currently precisely matched to the format of the battery cell. The same applies to the aging process, during which the cells are controlled and monitored in their properties. While the current systems are characterized by a high level of product orientation and specialization, especially with regard to cell contacting the modular setup of formation and aging chambers and the use of intelligent and adjustable carriers or trays indicates existing and further exploitable flexibility potentials.

### 4.4 Implementation strategies for different types of flexibility

The spectrum of flexibility opportunities between a streamlined, ramped-up battery production line for a specific cell format and a fully flexible battery cell production offering highly customized solutions is vast. Already in early stages of factory and process planning as well as conceptualization of logistics and warehouses this becomes very apparent. In each case different degrees of flexibility can be considered and realized accordingly. However, ensuring flexibility has its price that needs be taken into consideration. Thus, the general question arises as to how flexibility can be addressed so that initial efforts and investments ultimately pay off. The transformation of currently known LIB factories in a way that end-of-line products are variable and able to incorporate customer-specific requirements becomes the grand challenge. To set up a production system in this intersection of process optimization and flexible production, several approaches are feasible. Driven by the market demand, different flexibility areas can be addressed selectively or collectively by prioritizing different aspects of the product flexibility (Figure 7).

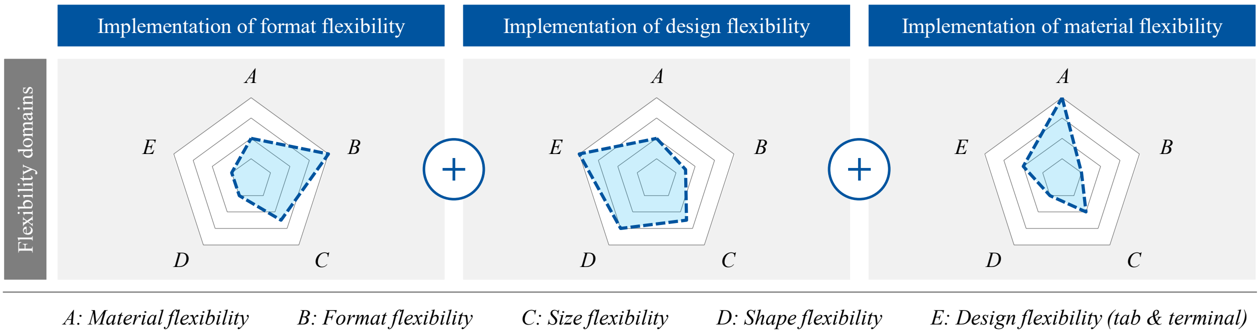


Figure 7: Overview of potential flexibility domains for implementation into battery cell production

A factory designed according to these flexibility areas differs from conventional configurations in several aspects, most notably in an even greater equipment complexity. The desired flexibility thus becomes the challenge of optimal coordination of individual equipment units within the production system, further extended to logistics and personnel, up to the underlying supply chains.

## 5. Conclusion

The demand for additional battery systems is primarily driven by automotive applications, but other new and promising segments such as aviation, wearables etc. are also increasingly emerging. Overall growth is driven by improved and application-specific battery cell technology. Flexibility areas in the battery cell design and their impact on process chain are critical to establishing a flexible production system capable of meeting the needs of multiple customers. Different implementation strategies can be pursued and practically implemented into a production system in order to leverage the potential of flexibility.

Flexibility potential can be tapped by focusing on selected formats, a defined design corridor and the ability to process a certain range of materials. The path to flexible battery cell production then can be paved by selecting or combining several of those flexibility areas. Other remaining challenges of supplying specific variants and changing market requirements can be overcome by adaptive electrode production and by expanding the equipment infrastructure within cell assembly and finalization as required. This not only enables on-demand production of different cell variants within one factory, but even parallel processing of individual production orders running in campaigns. Such flexible production systems hold the potential to handle multiple customer orders and reduce project-specific investment costs.

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