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Design of a Material Flow Method and Technology Procedure for Battery Cell Production in Mini-Environments

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Abstract

Due to the rising interest in electric vehicles, the demand for more efficient battery cells is increasing rapidly and immense production capacity expansions are announced in the next decade. Manufacturing of lithium-ion battery cells is complex and highly influenced by the environmental product conditions. Nearly along the hole value chain, the production processes take place in so-called clean and dry rooms to strictly control humidity and particular contamination. Cleanliness can be ensured with appropriate air management systems, while dry air handling is technically and energetically much more complex. To counteract this, the mini-environment approach reduces the amount of air, as the system is enclosed airtight in a process- and product-oriented manner. Mini-environments offer the possibility of replacing conventional clean and dry rooms through energy and cost savings, improved product quality and increased operator safety.

However, to rollout the mini-environment approach in battery cell production facilities, production methods and technologies must be developed and researched. Next to the machine level, especially the material flow level must be addressed and is key for the holistic integration of the mini-environment approach in production facilities. Moreover, due to cross-machine movements while maintaining constant and stable atmosphere conditions, there are currently no logistics or airlock solutions tailored for battery cell production.

This paper provides a method named MiniMaFlow including systematically developed solutions to enable modular and rigid material flow in mini-environments. The method is conducted to fulfill the cleanliness and humidity requirements with focus on innovation, costs, and sustainability. A first modular prototype has been designed to achieve detailed level for production research. With this, a holistic analysis and evaluation is conducted compared to the state of the art. In conclusion, a validated transferable potential heat-map and a use-case-specific quantitative evaluation for technology-implementation are shown as a result.

Keywords

Battery Cell Production; Clean And Dry Room; Mini-Environment; Intralogistics; Robotics & Automation; Potential Analysis; Prototype

1. Introduction to Battery Cell Production

The manufacturing of battery cells and their complex value chain involve numerous different process steps that depend on cell chemistry and design. Broadly categorized, it can be divided into three main areas: the electrode production, cell assembly, and cell finalization [1]. Additionally, alternative and innovative process technologies can be integrated in a complementary or disruptive manner. This requires detailed design of production facilities, considering the interrelationships along the value chain at the product, process, and factory level [2]. The active material in cell chemistry enables the desired effect of energy storage. Nickel-

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rich cathode materials as NCM811 are crucial for this, but they also react extremely sensitive to environmental conditions, especially to particles and moisture [3, 4]. For instance, a reaction with moisture leads to a negative impact on the battery's lifetime and capacity [5, 6]. Consequently, cell manufacturing requires precise and reliable controlled environments. A tailored and optimized process machine in terms of contamination control helps to minimize particle generation, temperature fluctuations and moisture ingress [7]. The factory level represents another crucial factor in battery cell production (BCP). Technical building services, clean and dry rooms as well as logistics concepts are mainly designed tailorwise nowadays. By designing modular factory layouts, the infrastructure can be used in a sustainable way and the strict requirements and regulations can continue to be met cost-effective in the future. [8]

The use of highly moisture-sensitive materials promises higher energy densities. The sensitivity of future cell materials is expected to increase due to trends like higher nickel content, the use of sodium-ion cathodes, pre-lithiated anodes, and solid-state batteries [9 –11]. Current cell factories operate with clean and dry rooms (CaD) to meet production-appropriate environment requirements. As shown in Figure 1, the necessary efforts are primarily determined by two factors: cell chemistry and production process. Another factor to consider is the exposure time of the material to the atmosphere [12]. As a result, CaD are individually configured based on product, process and production characteristics [7, 11–13]. The uncertainty regarding the exact choice of the material-specific dew point (dp) was considered in Figure 1, which is why representative dew point ranges are selected instead of specific dp parameters.

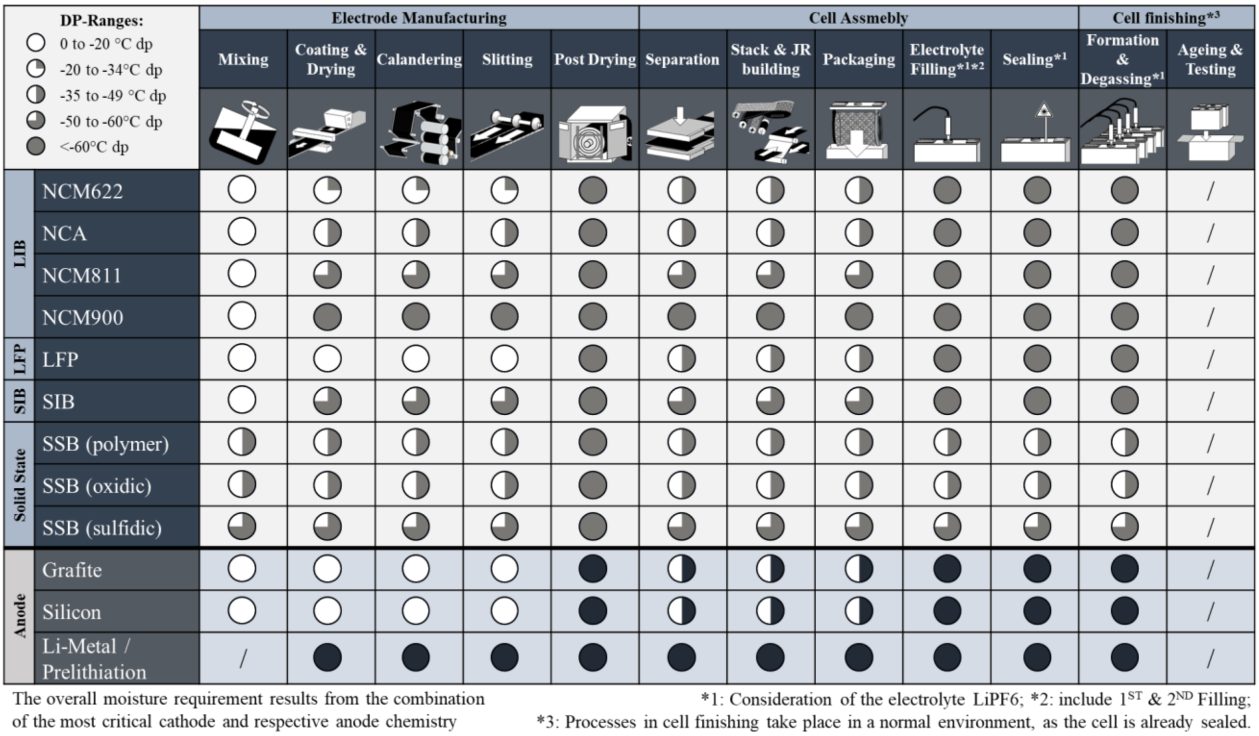

Figure 1: Dew point requirements for dry rooms based on moisture sensitivity of various cell chemistries evaluated by industrial application requirements and research experience.

Conventional CaD in BCP consume 26% to 53% of the total energy amount [2, 7, 14]. To promote promising, flexible, and cost-effective production approaches, there is a discussion about enclosed equipment technology in so called Mini-Environments (MiE). A MiE is a limited, separated product environment designed to protect the product from contamination [15, 16]. In scientific and industrial surveys, both main challenges and potentials for BCP in MiE have been identified. The top challenges include accessibility for the operator, long recovery times after machine opening and the design of physical interfaces for material handling [17]. In addition to that it is also important to acknowledge that MiE are characterized by a high degree of technical integration effort. For example, logistics processes within mass production lines for battery cells also pose a significant task. This complexity arises from the need to synchronize, coordinate, and connect numerous individual systems [18]. These logistics processes directly impact both the cost per unit and product quality [19, 20]. Regarding quantifiable benefits, including better control of environmental conditions, significant reduction in operating costs, and separation of the operator from the process and product, initial cost savings were calculated. Assuming the production of highly sensitive materials (-60°C dew point) and conventional CaD, cost savings of up to 77% over a period of 7 years can be achieved when using MiE instead of CaD [8]. Nevertheless, achieving this goal requires detailed and indispensable research efforts in this field [7, 8, 17]

2. Focus of Study and Approach

In this study, the objective is to elaborate an innovative material flow method including technological concepts, for future BCP in MiE. In addition, the investigation and evaluation compared to nowadays conventional clean and dry room production is conducted. To narrow the research focus, the MiE topic for BCP is tailored to material flow. Therefore, the following research questions will be addressed in this paper:

a) *Which requirements need to be fulfilled by a material flow method for moisture-sensitive and semi-finished products?*
b) *How should the material flow method and related technologies for the integration of MiE into a BCP be designed?*

The underlying approach for this paper could be described as following: 1. Derivation of requirements for material flow in MiE for the BCP sector 2. Identification of superordinate action fields 3. Evaluation and deficit identification of existing approaches 4. Development of a material flow method and technology procedure 5. Validation and quantitative analysis.

3. State of Research to Mini-Environments in Battery Cell Production

An overview of current requirements and trends in relation to the MiE and their direct and indirect impact on production suitability is compiled. In sum, sixteen requirements are derived for a technology-oriented production method in MiE. Known technologies, summarized through technical literature, product portfolio and patent analyses, are evaluated regarding the suitability according to the derived requirements. The research gap with focus on material flow in MiE for BCP is elaborated.

3.1 Mini-Environments

To contribute to the enhancement of energy efficiency in BCP, the holistic MiE approach has to fulfill various requirements. Particularly on the material flow level, different criteria must be met to ensure continuous product protection. These derived requirements stem from both scientific and industrial domains. Meanwhile, especially on research level first publications and concepts have been published to the technology-driven approach of MiE. [8, 35] These fundamental first conceptual designs are used for further application-oriented research and demonstration to further gain higher technology readiness level (TRL).

3.1.1 Derivation of requirements for the mini-environment approach in battery cell production with focus on material flow

The identified requirements (R) are described in a comprehensive way and list relevant references from literature, as reflects fundamental studies for objective assessment. All defined requirements are independent of each other. To structure all the single requirements, a cluster categorization is defined in a superordinate level. It is meant to organize the requirements in a logical order for better understanding and does not intend to definitely allocate all requirements.

R1 Market: The battery cell market is characterized by enormous growth rates in the next decade. This results in many opportunities for the optimization of the production technologies through e.g. breakthrough innovations or by using standardization and productization to be competitiveness. [21, 22] Therefore, *Innovation capability (R11)* is considered as one market requirement for setting up a MiE-oriented material flow approach. Moreover, the manufacturing know-how is predominating in established cell factories, while it is mostly top secret and forbidden to get a glance inside the factory to keep know-how ahead. Therefore, manufacturing know-how should be accessible for all upcoming factories. Thus, the *Technology accessibility (R12)* is considered as another requirement, which can be provided through e.g. funded projects by universities. [23, 24] In addition to the so-called Gigafactories, customer-flexible cell factories will be built up. [19, 25, 26] From this point of view, *Scalability (R13)* as well as *Flexibility (R14)* are further requirements in the context of MiE and its material flow solutions. In the long-term perspective, *Retrofittability (R15)* will play another crucial role, due to unavoidable usage of MiE mainly driven by product and process upgrades (e.g. in case of more stringent technical rules for hazardous substances) [17].

R2 Factory: A typical battery cell factory is characterized to its complexity within the planning and ramp-up-phase. Feasible planning requires a correspondingly high level of coordination and effort between the technology, factory and property planning team as well as other relevant specialist planners. Minimizing these interfaces mean *Integration Capability (R21)* is increasing [25]. The advantages lay in less complicated and fast planning phases resulting in project adherence to deadlines, costs and quality. To further support efficient and sustainable factory planning through systematic models and decision support systems, *Guidelines (R22)* help to achieve these goals [27, 28]. As a result, speed will be multiplied in the project phase through modularization, standardization and productization. Factory blueprints are described as a new approach on industrial level to factory design with a focus on scalability, modularity, and shortened timelines [29]. In general, segmental integration guidelines help to support the overall blueprint thinking.

R3 Production: According to BERGHOLZ, the basic functions of the production elements are *Transport and Storage (R31)* as well as processing [30]. In BCP, the processes are divided in the main sections *Electrode manufacturing (R32) Cell assembly (R33)* and *Cell finalization (R34)*. Each main section is again divided in different process steps. These processes are characterized by different atmosphere conditions to be maintained (see Chapter 1) and especially through the processed intermediate products and their characteristics in terms of design and their influence on handling equipment (e.g. electrode coils, cell stacks, magazines). According to BERGHOLZ several workstations (process equipment) can be described by a line or cluster. The set-up design of the machine equipment has to be considered in dependence to the material flow. The interlinking method between the workstations could be designed rigid or modular. As an example, and as already described in *R31,* these methods must handle fluctuations in production. Thus, storage requirements for buffering must be considered. While the hole value chain is provided in very rare cases from one turn-key supplier, the interface adaptability must be considered as the requirement *Interoperability (R44)*. [23]

R4 Product: Next to innovation on production level, the battery cell business is especially characterized by continuous improvements on product level. (see Chapter 1). To develop resilient MiE approaches, it is necessary to handle future cell materials as prelithiated anodes, nickel-rich materials, sodium-ion or sulfidic electrolytes. Therefore, F*uture readiness (R41)* is introduced as another requirement. Each atmospheric requirement regarding *Cleanliness & Dryness (R42)* has its own influence on the technology and approach to be derived. A particle in the sealed cell e.g. could lead to thermal runaway [20] while dryness leads to electrostatic charges and has an influence to the material choice regarding water diffusion and outgassing. *Atmosphere Control (R43)* is taken into account to ensure stable conditions in terms of particle control, safety and cross-contamination as well as to inline control exposition times of the material in specific environments to further gain research goals regarding humidity management.

R5 Technology: *Technology readiness (R51)* is taken into account in order to evaluate the approach in relation to the technological and application-oriented research gap. [31] Here, the field of robotics and automation in sensitive production environments is most relevant. The compatibility with the paradigm of *Industry 4.0 (R52)*, an interconnected manufacturing environment, is achieved by fully integrating the MiE and its material flow into the digital architecture of the manufacturing plant. The integration within the traceability system, which aims to identify, capture, acquire and aggregate relevant data, is a key requirement to match production data to the battery cell or the respective intermediate product and enable its digital twin [32]. Thereby, breaches in quality and the atmospheric conditions can be closely monitored and matched to the product at any point in time during the production process. The necessity arises from the research of critical exposure times of materials exposed to certain environmental humidity conditions. Thus, it could lead to identify more sufficient dew points and therefore less energy consumption due to less dehumidification. Moreover, this continuous availability of data is crucial for further analyses, process optimizations and regulatory requirements such as the battery passport. [33]

3.1.2 Relevant production methods and technologies

Since the requirements have been defined, several technology approaches from technical literature, product portfolio and patent analyses are described. Three main action fields were identified: Research approaches in the field of BCP (BR), Industrial approaches in the field of BCP (BI) and Cross-Industrial (CI) approaches developed to produce sensitive products, as semiconductor and pharma. Subsequently, these are evaluated in terms of their suitability according to the requirements. Different approaches are described in a compact way. For further details, reference is made to the underlying literature.

BR: According to PLOCHER ET AL. MiE as technically tight enclosures are similar to currently available gloveboxes [17]. They can be set up in a grey room and thus aim to replace large clean and dry rooms. It covers a comprehensive range of processes and is mainly focused by universities for material research. [34, 35]. According to HENSCHEL ET AL. their BR focuses on implementing agile methods in BCP [36]. This ensures adaptability across various applications. Using intelligent networking and modular design, the approach targets customized cells for different production scales, while demonstration is executed on a limited throughput. It relies on modular robot cells with inhouse-standardized interfaces to simplify complexity and minimize risks. According to HELLER ET AL. early designs on pilot level and the conceptual design for mass production have demonstrated that MiE for material flow are feasible in the electrode and assembly area [7, 8]. **BI:** In comparison to the scientific approaches, two identified industrial approaches will be described. The first approach addresses a multi-stage dehumidification system designed to control moisture in specific areas of dry rooms [37]. The system consists of a primary dehumidification section with an isolated interior space and one or more local dehumidification zones within it. Each zone has its own sealed MiE and dedicated dehumidification unit (DHU) to achieve lower humidity levels than the primary section. Material flow is realized through rigid interlinking in combination with moisture-blocking housing extensions and first air curtain mechanisms to maintain desired low-humidity conditions. The second approach focuses on specific process automation solutions for BCP, including a driverless transport system [38, 39]. This system is tailored for seamless material transportation within the energy cell manufacturing sector. It features a transport chamber that can move and be sealed, with a secure opening for docking with encapsulated machines. Once connected and unlocked, materials can be automatically transferred between the machine and transport chamber, optimizing production workflows. Further industrial approaches are from Toyota [40] and Weiss Klimatechnik GmbH [41]. **CI:** A review of specific cross-industry approaches shows that in the semiconductor and pharmaceutical industries are requirement-comparable and already very advanced. In the semiconductor industry, maintaining utmost cleanliness in production is crucial, necessitating operations in clean rooms. To minimize particle contamination, a MiE solution was applied. Semiconductor wafers are transported in sealed containers, opened only within specific process machines like Rapid Thermal Processing (RTP) systems. Isolated transport technologies are already standardized and integrated, like SMIF (Standard Mechanical Interface) containers [42], with modified designs for larger wafers like FOUP (Front Opening Universal Pods) and FOSB (Front Opening Shipping Boxes). Transport methods include manual, automated guided vehicles (AGV), or overhead hoist transport (OHT). [43] In pharmaceutical production, handling poses risks to employees and materials in cleanrooms. The production necessitates suitable equipment, especially for the high-value and hazardous materials. Customized transport robots are employed for safe handling and transportation between production and storage areas through peripherals to maintain optimal conditions during transport. [44] In addition, materials are transferred without contamination via so-called Rapid Transfer Ports (RTP). Based on this airlock technology, material or instruments can be brought into or out of an isolator in a sterile manner.

3.2 Summary and Evaluation of Approaches

The research gap is derived based on Table 1. The requirements introduced have a discrete character. They can be considered not fulfilled, partially fulfilled, or completely fulfilled. To allow reproducibility, a requirement is fulfilled when the approach fulfills the requirement described in a holistic way. In the field of **BR** the glovebox approach meets the requirements for BCP. The characteristics are limited to the laboratory level and have not yet been applied in scalable scenarios. The other approaches from HENSCHEL and HELLER pursue fundamentally transferable methods for the material flow for specific processes. Especially the TRL indicates that there is still a production-oriented research gap. The patent-based battery-related material flow methods in **BI** are described for special use-cases. There is no public information regarding its application and therefore validation in terms of functionality. Also, there are no guidelines for integration into a factory and electrode manufacturing processes aren't considered. In addition, atmosphere control systems aren't described in detail. To summarize, industry-related approaches are limited on concept level. Finally, long-term established and researched material flow methods as well as related technologies exist in the cross-industry sector (**CI**). The technology transfer is not given to the battery sector due to its production-driven requirements.

Table 1: Harvey Balls Matrix – Assessment of existing approaches regarding requirement fulfilment

Battery-specific requirements for material flow in mini-environments			Approach						
			Battery-Research			Battery-Industry		Cross-Industry	
			[36]	[7, 8]	[34, 35]	[37]	[38, 39]	SEMICON.	PHARMA
Requirement	R11	Innovation capability	●	●	○	●	●	○	○
	R12	Technology accessability	●	◑	●	○	○	◑	◑
	R13	Flexibility	◑	◑	○	◑	◑	●	●
	R14	Scalability	◑	●	○	●	●	●	●
	R15	Retrofittability	◑	◑	○	○	○	◑	◑
	R21	Integration capability	●	◑	●	◑	●	◑	◑
	R22	Guideline	○	◑	◑	◑	◑	●	●
	R31	Transport and Storage	◑	●	◑	◑	●	●	●
	R32	Electrode manufacturing	◑	◑	●	◑	◑	○	○
	R33	Cell assembly	◑	◑	●	◑	◑	○	○
	R34	Cell finalization	○	○	●	○	○	○	○
	R41	Future readiness	◑	◑	●	◑	◑	●	◑
	R42	Cleanliness & Dryness	◑	◑	●	◑	◑	●	●
	R43	Atmosphere control	○	◑	●	◑	◑	◑	◑
	R51	Technology readiness	◑	◑	●	◑	◑	●	●
	R52	Industry 4.0	◑	◑	◑	○	◑	●	●

○ not fulfilled / not accesseble ◑ partially fulfilled ● completely fulfilled

In summary, none of the presented methods and technology approaches fully meet all the evaluation requirements. Overall, no specific solutions are described to support decision making for mini-environment -oriented material flow in the battery sector. Furthermore, no technologies are existing to fulfill all market requirements. Moreover, the introduced technologies don't have the maturity for production readiness. Atmosphere control systems, including digitalized approaches aren't implemented to conduct application-related research. The aim of this paper is therefore the derivation of a new material flow method and the development of the necessary technologies and procedures to enable BCP in MiE.

4. Concept Design of the Mini-Environment Material Flow Method (MiniMaFlow)

Based on the requirements derived in chapter 3, the module specification of the method was carried out through clustering of the requirements from chapter 3.1.1. The overall structure is divided into three superordinate modules. The specific requirements are linked to the three main modules *Initiation* (R13, R14, R15, R31, R32, R33, R34, R41), *Analysis* (R21) and *Design* (R11, R12, R22, R42, R43, R51, R52). The initiation module collects the data and defines the characteristics for the subsequent analysis and design module. Eight identified requirements from chapter 3.1.1 are considered in the initiation module. The analysis module evaluates the data and requirements in terms of relevant target criteria such as costs and feasibility for battery cell production and interacts with the design module. Here, one method-related requirement was considered. To consider a guideline for a reproducible application, a circular approach as a structured planning procedure is applied in the design module. Starting at the product level, the module shows the interpendencies between the air management and relevant interfaces in production. Thus, comprehensible decision making in terms of modular and rigid material flow can be carried out [45]. Due to the individuality of each intermediate product within the value chain and its effect to the material handling in case of loading and unloading, the *MiE_* boxes in Figure 2 form the technology-driven integration of the necessary intralogistics systems. Appendix 4 shows the method-integrated developed modular technology procedure to enable the application of MiniMaFlow. The design module synthesizes seven related requirements. These requirements are the *MiE_* technology-driven requirements in order to achieve their necessary maturity for manufacturing readiness. Overall, Figure 2 represents the elaborated MiniMaFlow which supports the planning and design of a mini-environment conducted BCP.

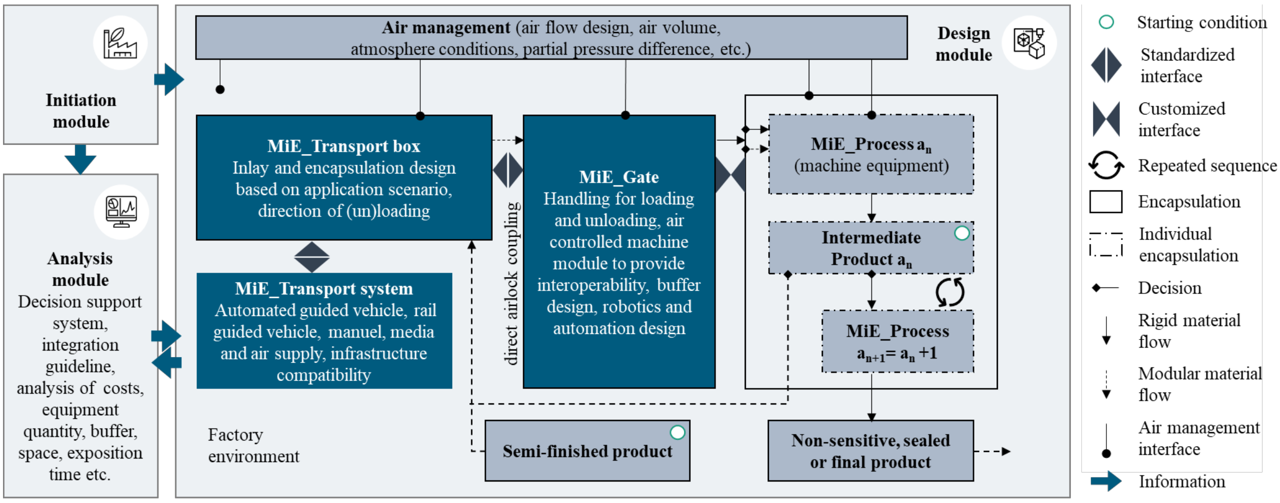

Figure 2: Mini-environment material flow method for battery cell production (MiniMaFlow)

As shown in Appendix 4, material flow can be carried out in a rigid or modular manner. The innovative modular approach is not state of the art and includes a transport system coupled with an air controlled MiE. A first technology procedure has been conceptualized based on requirements engineering methods, which is exemplary represented through the *MiE_* boxes in figure 2. Similarly, a TRL 7-targeted and developed prototype is shown in Appendix 4 and will be field researched in future. The advantage of the system introduced lays in a manufacturer-independent interface design due to potential of standardization. Moreover, the deep technology is a removable housing element arranged and designed in such a way that contaminated surfaces of the transport housing element and the machine module seal each other during coupling and airlock opening. The dew point selection (air management) is an example and was selected based on the application scenario in chapter 5. It is used for detailed potential and cost analysis.

5. Application

As shown in Appendix 1, the »FFB PreFab« in Münster is chosen as the validation scenario. The »FFB PreFab« assembly is capable to produce 8 pouch cells per hour automatically. The pre-assembled cells are sealed and filled in one of the so-called innovation spaces, a separate clean and dry room accessible via an air-conditioned intralogistics corridor. The basic scenario under consideration assumes a -60°C dp in all three rooms (pre-assembly, intralogistics, innovation space). MiniMaFlow was validated in the 2nd scenario. The intralogistics corridor and the innovation space are conditioned to -20°C dp, while -60°C dp is maintained in the point of interest with the MiE approach for the transport and process module within the innovation space, as shown in Appendix 1. The MiE processes are conditioned according to the cascade principle with locally integrated DHUs. The pre-assembly room will further take place in -60°C dp. This decision was made based on the derived methodology in this paper, mainly driven by the small amount of space available to retrofit the assembly machines. The overall goal in the 2nd scenario is to control the atmosphere that there is zero exposition time of the materials to higher dew points than -60°C dp (zero contamination approach). Appendix 2 show the analysis and detailed cost comparison between the two scenarios. Based on the CapEx and OpEx calculation according to HELLER ET AL., it can be shown that the annual cost savings amount to 205.736 €, whereby the majority can be allocated to energy costs. Overall savings of 1.840.154 € can be achieved over a utility time of 8 years. All detailed cost assumptions and uncertainties are shown in the "Comment to assumption" column in Appendix 2.

Furthermore, as an integrated element in the value chain, the MiE could represent an interface to a large part of the BCP processes and production areas. For this reason, a qualitative evaluation method is selected that provides a comprehensive overview of the strengths and weaknesses of the concept based on three production-oriented key performance indicators. The comparison between the state-of-the-art BCP and the approach introduced in this paper is visualized using a so-called heat map in Appendix 3. The heat map can help to identify potentials between the processes and operation fields. These conclusions can be used during further development to ensure appropriate use.

6. Discussion & Outlook

The research question a) could be answered and led to the establishment of sixteen independent requirements. Subsequently, MiniMaFlow was derived. Moreover, a concept of the related technology procedure was elaborated for a modularly applicable material flow in MiE. In addition, a guideline-based circular planning structure was defined to support the value chain design. Herewith, research question b) could be answered. Our study provides the first quantitative cost analysis of the deployment of MiE compared to CaD. However, the elaborated MiniMaFlow is still limited on concept level, why further research activities aim on the specification of each module and its interactions among each other. Especially the air management is crucial and needs detailed research. The main limitation is that physical validation isn't conducted, which is why the solution approaches in this paper are subject of ongoing development projects. The investigation of the technology in application is needed to further scale the MiE material flow approach to factory level and to support knowledge generation on moisture management. MiniMaFlow supports the future planning of the FFB and has a significant contribution to the savings in operating costs, directly resulting in lower cell costs. Overall, the MiE-oriented material flow approach supports the initiation of a new era in BCP, fostering improvements in quality, production yield, efficiency, and costs.

Acknowledgements

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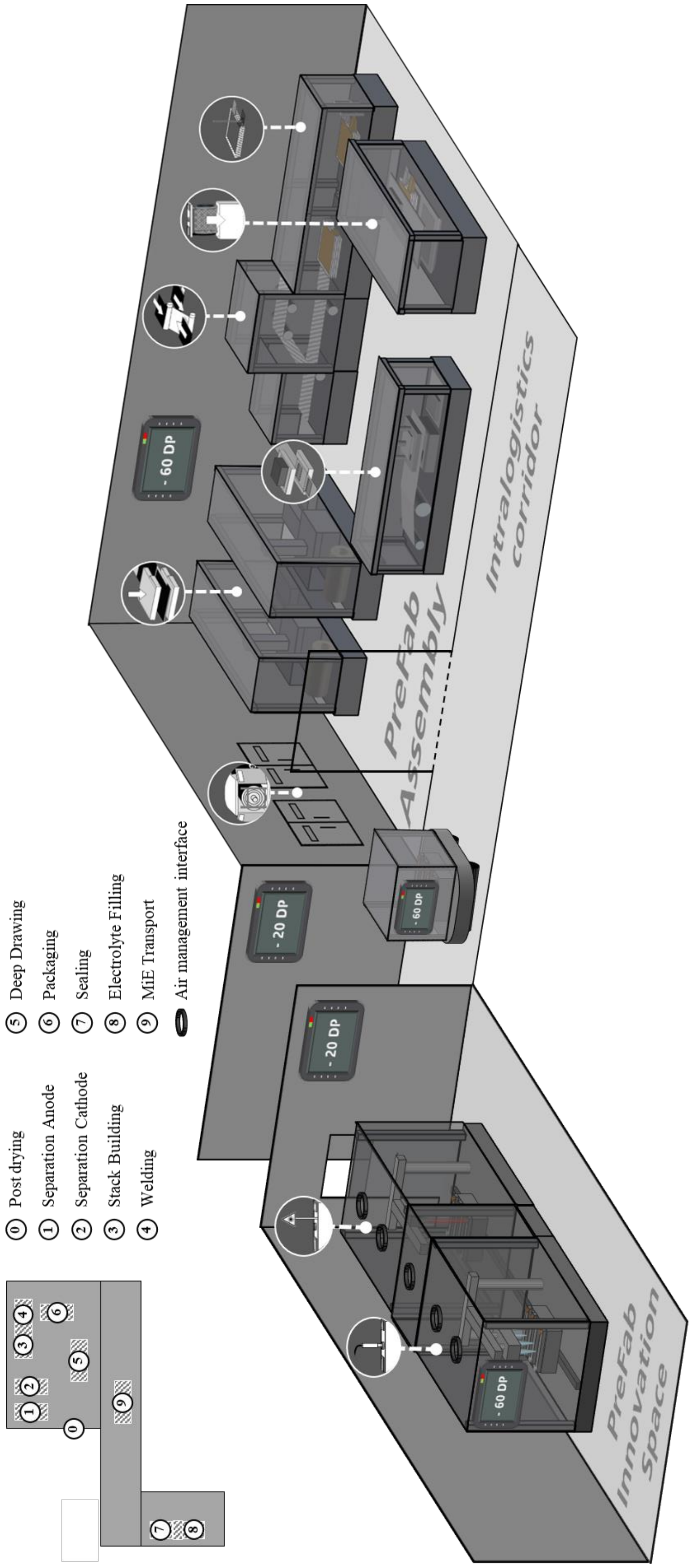
Appendix 1: »FFB PreFab« pouch cell assembly (2nd scenario shown)



Appendix 2: Quantitative cost analysis of the pouch cell assembly scenario

No.	Cost position	Scenario 1 (CaD)	Scenario 2 (MiE)	Comment to assumption
1	**Capital Expenditures***	**8.085.280,20 €**	**7.891.017,03 €**	
1.1	Equipment machines	Reference scenario for cost comparison	1,28%	Increased costs for Scenario 2 through the adaption of the upgraded MiE material flow system; Driven by investment in robotics and automation: 2x transport MiE, transport system, MiE gate, airtight machine enclosure
1.2	Dehumidification systems		-26,10%	Pre-assembly unchanged; DHU-downsizing to -20°C dp in intralogistics corridor, DHU-downsizing to -20°C dp in Innovation space (one DHU used for both rooms); 2x small DHU added for -60°C dp in process MiE
1.3	Planning		0%	Costs for scenario 1 calculated based on HAOI-Phase 3-5; Further comparison needs detailed planning to identify the detailed cost structure in planning efforts. Therefore no difference for this cost element assumed
1.4	Installation and commissioning		-17,58%	Less installation efforts; Effort reduction due to less piping and handling of smaller components and DHUs
1.5	Employee		0%	No changes in number and scope of training courses and seminars expected, Operator training efforts unchanged in the 2nd scenario
1.6	Area		0%	The Layout was already defined. Therfore no changes in the production layout between both scenarios. Trend: Less space needed due to smaller DHUs on the technical area.
1.7	Clean and dry room		0%	No significant changes in clean and dry room design expected (wall, floor, etc.)
2	**Operational Expenditures per year***	**1.055.147,84 €**	**849.411,47 €**	
2.1	*Operation per year*	Reference scenario for cost comparison		
2.1.1	Employee		-9,84%	Per year and operator, clean and dry room clothing of up to 8.000€ are estimated for scenario 1. No differences to scenario 2 expected in this case; Further improvements due to higher automation degrees to implement MiE-Gates (loading & unloading). Expected time efficiency of 6min per hour due to less manual handling efforts
2.1.2	Energy consumption		-29,11%	The reduction of the energy costs is driven by the small amount of conditioned air volume for scenario 2; Energy consumption of the machines itself is not considered; Electrical energy costs: 0,3€/kWh, Operation days: 320
2.1.3	Emissions		-29,11%	German emissions factor: 0,434 kg/kWh (2022), 45 €/tCO2
2.1.4	Setup		potentially high cost savings	Faster reconditioning and recovery times after shut-down, what directly influences the possible production throughput per year and therefore the added value; Further research efforts are necessary to quantify the impact of mini-environments to the overall production throughput.
2.1.5	Scrap		potentially high cost savings	For example in case of unforeseen DHU failures material could be safed in the Transport-MiE due to intermediate storage ability. Also higher A-grading rates are expected due to tailored air flow through MiE (Point of interest supply); Further research efforts are still necessary to quantify the impact of mini-environments to the scrap rates
2.2	*Maintenance per year*			
2.2.1	Cleaning		marginally higher costs expected	Further research efforts necessary; Cleaning methods not yet defined sufficiently and investigated
2.2.2	Process equipment		marginally higher costs expected	Further research efforts necessary; Challenges in maintenance due to the MiE approach are still being investigated
2.2.3	Air handling unit		20,00%	More components to maintain in scenario 2 result in higher maintenance efforts and costs
2.2.4	Production downtime		potentially high cost savings	Faster reconditioning and recovery times after shut-down, what directly influences the possible production throughput per year and therefore the added value; Further research efforts are necessary to quantify the impact of mini-environments to the overall production throughput.
		CapEx Difference overall	**194.263,17 €**	
		OpEx Difference per year	**205.736,37 €**	
	Total cost savings in 8 years through MiE approach in the defined use case		**1.840.154,14 €**	

*Detailed cost-breakdown not provided due to confidential disclosure of the individual elements

Appendix 3: Potential analysis for MiE in BCP

Heat-map comparison between production in conventional CaD as reference and production in MiE based on the material flow design elaborated in this paper. The matrix serves as a possible guideline and application orientation. However, each use case must be considered individually and may vary.

Scale: 1 much worse; 2 worse; 3 marginally worse; 4 neutral / not useful; 5 marginally better; 6 better; 7 much better

	Electrode Manufacturing					Cell Manufacturing							Logistics				Operation Scenarios			
	Mixing	Coating & Drying	Calandering	Slitting	Post drying	Separation	Stack & JR building	Packaging	Electrolyte filling	Sealing	Formation + Degasing	EOL + Sorting	Cross-factory production	Intralogistics transport	Storage Areas	Intermediate Storage	Maintenance	Partial load (weekend, night)	Production fluctuations	External shipping
Costs	4	5	5	5	3	6	6	6	6	6	3	4	6	7	3	5	5	6	5	5
Quality	4	5	5	5	5	5	5	5	5	5	4	4	6	6	4	5	4	5	4	6
Safety	4	5	5	5	5	7	7	6	7	6	5	4	5	5	5	5	4	4	4	4
Ø*	4	5	5	5	4,33	6	6	5,67	6	5,67	4	4	5,67	6	4	5	4,33	5	4,33	5

*equal weighting

Electrode Manufacturing: The mini-environment approach requires a high degree of automation and robotic solutions for heavy electrode coils. It tends to have a positive impact on electrode production. The advantages are particularly exploited for moisture-sensitive materials.

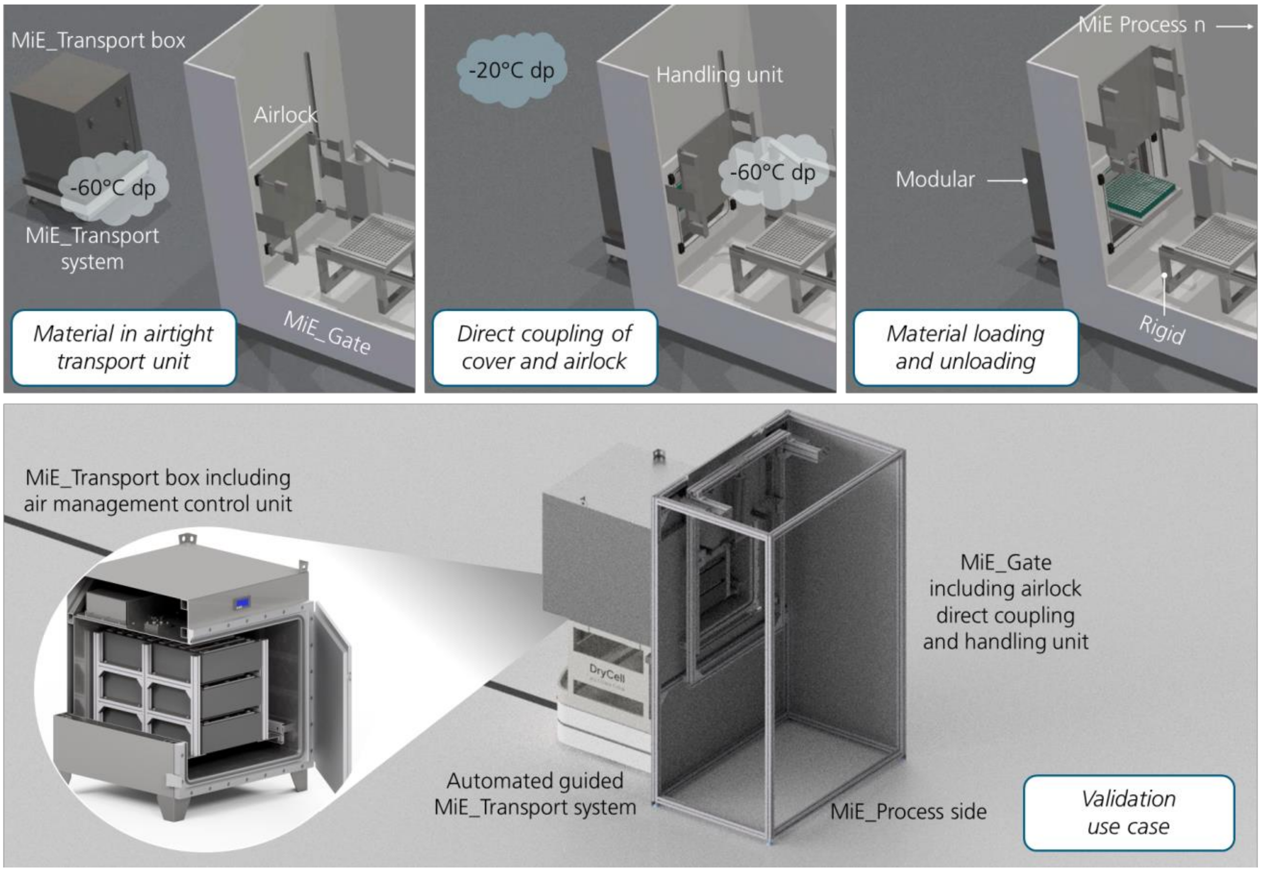
Cell Manufacturing (Separation to Sealing): Mini-environments are already showing clear advantages in cell assembly due to the high standards of cleanliness and dryness. In particular, the stresses and safety conditions for the operator can be minimized in addition to the high energy consumption.

Formation + Degasing, EOL + Sorting: Temporary hermetic sealing of the cells with a plug as an alternative approach for degassing, MiE already in use

Logistics and Operation Scenarios: Advantageous use holistically in the logistics. For larger storage areas, conditioned rooms may be more cost-efficient than stacking individual MiE. Furthermore, MiE for transport are useful for cross-factory applications due to reusable design.

Appendix 4: Engineered modular technology procedure for mini-environments

Standardized MiE-docking ensuring zero contamination between inner and outer atmosphere. The sequence for transferring the sensitive intermediate products from the MiE_Transport box to the MiE_Gate is shown.



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