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Evaluation of Logistic Concepts for Flexible and Automated Electrode Production

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Abstract

Several production steps characterize the manufacturing process of electrode materials for battery cells. Due to new technological developments in logistics, the process steps can be connected differently having an impact on the flexibility of the production. For example, the material flow can be adjusted more difficult by linking the plants with fixed conveyor belts. Reducing personnel in clean and dry rooms is essential for rising economic efficiency. This results in new requirements and challenges for logistic planning. This work shows a concept for designing and evaluating intralogistics processes in the tension between flexibility, automation, and economic efficiency.

Keywords: Intralogistics; Electrode production; Planning of flexible intralogistics processes; Automation of intralogistics processes

1. Introduction and Motivation

The energy transition has brought about significant changes in the automotive industry, with the increased adoption of electric vehicles (EVs) powered by batteries [1]. The battery cell is a crucial component of an EV, and producing high-quality and affordable battery cells is essential to widespread EV adoption. Battery cell manufacturers are building more factories to meet the increasing demand for battery cells [2, 3].

However, battery cell production faces numerous challenges, including the need for specialized dry room environments resulting, amongst others, in high costs and non-standardized logistics processes, such as the coil handling into the machines. To reduce the overall cost of EVs, more efficient and cost-efficient battery cell production processes are necessary [4]. As requirements change due to new research results and at the same time due to a growing number of different customers, battery cell production must be designed flexibly to meet these needs. Material flow flexibility and variant flexibility are critical in serving customers with diverse requirements and responding quickly to research developments. At the same time, battery cell production must be cost-efficient. Automated solutions for logistics processes can reduce costs in the long term. However, there is a trade-off between automation and flexibility regarding logistic resources, and the question arises as to when automation becomes cost-efficient and how to evaluate flexibility [5].

To address these challenges, manufacturers are exploring ways to increase the efficiency and cost-efficiency of battery cell production. One way is to increase the automation of production processes to reduce the overall cost of production. However, this comes at the expense of flexibility, which is necessary to respond quickly to changing customer requirements and research developments [6].

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Therefore, there is a need to identify the break-even point for automation in battery cell production and evaluate the relevant criteria to make optimal decisions between automation and flexibility. This paper aims to provide insights into the evaluation criteria and the break-even point for automation in battery cell production.

2. Fundamentals

The following discusses the process chain of electrode production as one part of battery cell production and the associated challenges. This is followed by a detailed description of the logistic processes within production in general and electrode production in particular. In the context of the present work, the term automation and flexibility will then be discussed.

2.1. Requirements for logistics within electrode production

The production of lithium-ion batteries consists of several closely interlinked production steps, which are divided into electrode manufacturing, cell assembly, and cell finalization. The complexity that arises is primarily characterized by a large number of process parameters and interactions involved in electrode manufacturing [7].

One important aspect is that moisture and particle contamination in the electrochemical compartment during battery cell production can lead to a degradation of battery performance [8]. While it is common for cell assembly to take place in dry rooms with a dew point of -40 to -60 °C [9], it is also necessary for moisture-sensitive electrode materials to operate the electrode production in a dry room with low humidity levels to prevent degradation of the active material, which can lead to poor battery performance [8]. When it comes to all-solid-state batteries or the processing of metallic lithium for use in lithium-ion or all-solid-state batteries, the issue of humidity goes from being a performance issue to a safety issue [10, 11].

Therefore, minimizing the presence of humidity to maintain battery performance is critical, which is why the production environment must be carefully controlled to ensure high-quality electrodes [9, 12]. The close interlinking of individual processes and the spatial conditions of clean and dry rooms place high demands on logistics concepts and material flows.

Logistic processes should facilitate the transformation of goods. Moreover, the emphasis is solely on the fundamental functions of storage, transportation, and handling, along with the ancillary function of packaging, which facilitates transporting, handling and storing commodities [13].

The present work focuses on the process chain for electrode production as one part of battery cell production. The process begins with mixing the slurries for the electrodes. The substrate foil is then coated with the slurry and dried. The electrodes are further calendered, then slit, and finally dried again. Fig. 1 shows the associated logistics processes along the material flow, starting with the transport process from the warehouse to the airlock and ending with the transport process from the airlock to the warehouse.

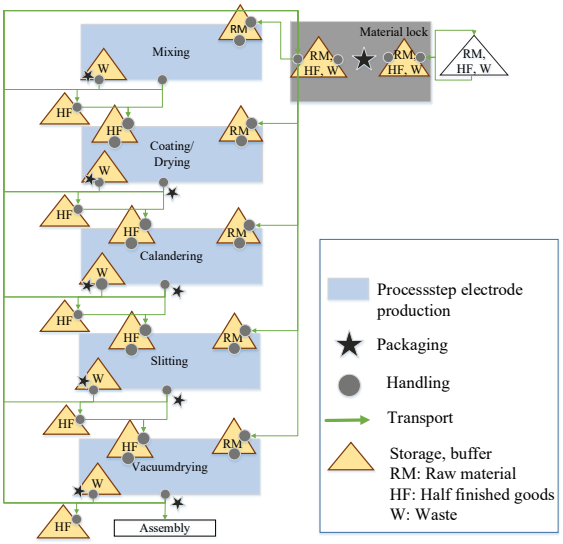

Fig. 1. Logistic processes in the electrode production.

In addition to Fig. 1, in Table 1, the processes are listed separately and assigned to the logistic process categories.

Table 1. Based on Pfohl 2018 [13] and adapted to the electrode production.

Store/buffer – temporal transition	***Transport – location change***		***Handling – location change***
	From	*To*	
Raw-material	Ware-house	Material lock	Material lock: Handling in/out of packing/cleaning station
Half-finished -goods	Material lock	Machine	Production: Handling in/out of providing area
Waste	Material lock	Ware-house	Production: Handling in/out of the machines
	Machine	Logistic resource	Production: Handling in/out of buffer
	Machine	Material lock	Production: Handling in/out of the waste area
	Machine	Machine	
Packaging – enable/facilitate the transport, handling, and storage of goods			
Material lock: Repack material in a clean-/dry room suitable container			
Production: Packaging of waste			
Production: Packaging of half-finished goods			

When planning the logistic processes and the resources used for this purpose, particular challenges are encountered within electrode production. All material in the production needs to be buffered, transported and handled in clean-/dry room atmosphere to ensure the requirements for electrode production. Since hazardous substances are processed, and materials, as well as different half-finished and finished products, have different sizes or are stored in separate containers, this must also be considered in the logistic concept. The transport, handling, storage, and packaging must cope with this. This may require different equipment. The automation to handle these is possible but not standardized yet. Since there are numerous manufacturers of production and logistics equipment, there exist numerous interfaces that lack standardization.

2.2. Automation in electrode production

In electrode production, the automation of logistics plays a crucial role in ensuring a smooth process and achieving high production output. According to DIN V 19233, automation is "the equipping of a device so that it operates as intended, wholly or partially, without the involvement of humans" [14]. Automating logistical processes can help improve the efficiency and quality of the overall system. By automating logistics processes, materials, and products can be transported faster and more effectively. Automated transport vehicles can be used for this purpose, for example. This can be expected to save time and labor. Another advantage of automating the logistical processes in electrode production is the improvement in quality. The use of automated systems can reduce sources of error and increase accuracy. For example, errors in the transport of materials can be avoided by having automated systems take over this task. Table 2 gives an overview of the possibilities that exist for partial and complete automation of logistics and their task areas in electrode production.

Table 2. Possible logistic solutions for electrode production.

Task area	*Manifestations and examples*	
Transport	Continuous conveyer	Roller conveyor Chain conveyor Belt conveyor
	Discontinuous conveyor	Lift trolley Forklift AGV
Handling and Packaging	Manuel	Balancer Teleoperators
	Programmed	Loading portal Industrial robot

2.3. Flexibility in electrode production

From a logistics perspective, flexibility describes the adaptation without additional effort that can be selected and applied in a focused approach depending on the planned and anticipated situation [15]. In this context, a flexibility corridor defines the range of action in which a system can adapt to changes in the environment for all possible future scenarios [16].

With regard to electrode production, the flexibility types material flow flexibility, quantity flexibility, and variant, as well as program flexibility, according to Sethi and Sethi [17], are focused, whereby the last two were grouped in the present work. Quantity flexibility describes the ability to remain economical with different degrees of utilization. In relation to electrode production, as exemplified in Table 3, this is relevant, for example, to serve different customers with varying quantities of order. Material flow flexibility describes the ability to efficiently guide components on different paths through the system, and the variant and program flexibility describes the capability to easily introduce new products and to produce different variants without decreasing the stability of the system [17]. Furthermore, Table 3 shows all three types of flexibility considered, for which issues they are relevant to choose and integrate into production.

Table 3. Flexibility with regard to electrode production.

Quantity flexibility	*Material flow flexibility*	*Variant-, and program flexibility*
Reaction to changes in order quantities; Serve multiple customers with different order quantities	Different customer requirements regarding product and half-finished goods; Specialization of individual production sites on individual process steps; Transport between plants of different half-finished goods	Response to research findings regarding materials and half-finished goods; Serving different customer requirements

3. Evaluation of logistic systems

When selecting suitable logistics systems, it is relevant to be able to evaluate the potential systems. Depending on the application, various evaluation aspects play different roles. In Chapter 2, the importance of the criteria flexibility, automation, and cost efficiency was described in relation to electrode production. Most approaches to evaluate factories currently focus on the production system and not on the logistics system in particular. In addition, no comprehensive approach has been found that takes into account both cost and process aspects when evaluating the flexibility and automation of logistics systems. For example, Gudeus [18] provides an approach for logistics systems. It starts with a feasibility analysis of possible technologies. The systems are evaluated for technical feasibility, fulfillment of performance requirements, compliance with general conditions, restrictions and constraints, and feasibility within the specified period. Furthermore, this approach includes a performance comparison as well as an economic efficiency comparison. In the final step, the solutions that are technically and economically equivalent are compared within a utility analysis on the basis of defined evaluation criteria such as service quality, availability, flexibility, compatibility, manpower intensity, damage risk, and cost risk [18]. Gudeus' [18] approach is very comprehensive in its evaluation criteria but does not put a specific focus on flexibility and automation and relates these to cost. In particular, no concrete definition for the evaluation of flexibility and no specification on types of flexibility is given. His approach is, therefore, too general to be able to evaluate the logistics systems within electrode production under the challenges and objectives identified in Chapter 2. Therefore, there is a need for further research and development, especially with regard to the particular requirements in the field of logistics.

In addition to the approach of Gudeus [18] to evaluate a whole logistic system, further approaches to evaluate the flexibility of production and logistics systems were found. Some are based on simulations like PLANTCALC [19], while other software applications, like ecoFLEX [20] or DESYMA [21], are based on a scenario-based approach. There is also another available approach known as the fuzzy logic approach [22]. These approaches, however, are very data-intensive and time-consuming, as they require extensive data collection. In connection with the evaluation of

flexibility, the EPEI (Every part, every interval) is often used as a KPI. The EPEI combines the flexibility type's product, quantities, and operational flexibility. It indicates the time interval required to have produced all the envisaged variants once. However, since the EPEI focuses on production, it is not suitable for evaluating the degree of flexibility of logistics resources [23, 24].

In the following, an approach is presented which, based on the target criteria flexibility, personnel intensity in connection with automation, performance as well as economic efficiency of Gudeus [18], concretizes these and brings them into a context of electrode production.

4. Methodology for evaluation of logistic concepts

As Chapter 3 has shown, there is a need for a more advanced methodology for planning logistics processes that link and evaluates the target criteria of automation, flexibility, and costs for the logistics use case in electrode production. The developed methodology is a decision-making method for the evaluation and optimization of logistic concepts. It is based on the concept of the trade-off between automation, flexibility, and costs. For this purpose, first, the necessary input parameters are described. Furthermore, the procedure of the method is shown and the evaluation criteria are described. Finally, Chapter 4.2 presents three scenarios for the design of logistics processes in electrode production, which are subsequently evaluated.

4.1. Input and evaluation parameters

In order to make various logistic concepts for electrode production economically evaluable in terms of automation and flexibility, various parameters must be defined at the initial stage. The input parameters are divided into **production, automation, flexibility** parameters, and information regarding the **cost** baseline.

On the one hand, a production speed designed for this purpose as well as the observation period and the shift schedule, must be defined. On that basis, the production output can be calculated. In the case of electrode production, the output in the present work is determined in meters.

Furthermore, the total number of logistic processes which can be automated need to be defined. Fig. 1 shows the logistic processes to be considered in electrode production. A total of 103 logistics processes were identified.

Since no distinction can be made between manual and automated processes for pure time transition within the buffers, these are not considered further in the rest of the method. Of the remaining 82 processes, 10 are packaging-, 42 are handling- and 30 are transport processes. Depending on the systems selected for the use case, the number of processes that can be automated to fulfill the logistics tasks is specified. In the next step, the resulting flexibility is determined for the envisaged systems with regard to the flexibility types described in Chapter 2.4. For each type of flexibility, evaluation criteria are defined based on which the respective system is evaluated by means of an evaluation scale of 0 to 2. The ratings are classified as follows.

- 0 = No possible flexibility
- 1 = Flexibility partially possible
- 2 = Needed flexibility is possible

The evaluation criteria, as well as the determination of the overall flexibility of a system, are shown in Table 4.

Table 4. Criteria for the evaluation of flexibility.

Quantity flexibility Q_f	Change in the number of transport system $Q_{1transport}$
	Change in the speed of transport system $Q_{2transport}$
	Add the transfer point $Q_{3transport}$
	Change the number of handling units $Q_{4handling}$
	Change the speed of handling units $Q_{5handling}$
	Change the number of handling units $Q_{6packaging}$
	Change the speed of handling units $Q_{7packaging}$
Quantity flexibility: $Q_f = (Q_1+Q_2+Q_3+Q_4+Q_5+Q_6+Q_7)$	
Material flow flexibility M_f	Change of transport route $M_{1transport}$
	Add the transfer point $M_{2transport}$
Material flow flexibility: $M_f = (M_1+M_2)$	
Variation flexibility V_f	Variation of the loading aids $V_{1transport}$
	Replacement of the load support $V_{2transport}$
	Add the transfer point $V_{3transport}$
	Variation of the loading aids $V_{4handling}$
	Replacement of the load support $V_{5handling}$
	Variation of the loading aids $V_{6packaging}$
	Replacement of the load support $V_{7packaging}$
Variation flexibility: $V_f = (V_1+V_2+V_3+V_4+V_5+V_6+V_7)$	
Total flexibility $F_t = G_f+M_f+V_f$	

Next, a **cost basis** must be specified so that the possible solutions can be evaluated in terms of costs. Investment costs for manual and automated resources for the transport, packaging, and handling processes are entered.

Furthermore, the operating costs per hour for the logistic resources of the respective selected system as well as the operating costs per employee, taking into account the increased costs due to the work in clean/dry rooms, must be defined. The composition and derivation of the hourly rates are not the focus of this work. For this publication, values were assumed as examples.

For the subsequent evaluation, the **degree of automation** is determined based on the number of possible processes to be automated in relation to the total number of logistics processes. Next, the **degree of flexibility** is determined, which is given by Equation (1). It indicates in percentage how flexible the selected systems are for a previously defined flexibility corridor. It results from the flexibility input values from Table 4 and the highest possible rating, which is 2, as can be seen in Chapter 4.1. Total flexibility can be calculated according to the description in Table 4. The total number of flexibility criteria is 16, which can also be seen in Table 4.

$$Degree\ of\ flex.[\%] = \frac{Total\ flexibility * 100}{Highest\ evaluation * Number\ of\ evaluation\ criteria} \quad (1)$$

After the target criteria automation and flexibility have been evaluated, **the cost calculation** will be discussed in the following. Therefore the demand for automated and manual resources is evaluated for the use case depending on the logistic process. Subsequently, the number of employees and the utilization of the resources as well as the defined buffers, are calculated. The number of logistic resources and their utilization can be determined using various planning tools

such as static or dynamic simulations. However, this is not focused on in this paper. Together with the cost basis, the total investment costs as well as the operating costs and, derived from these, the costs per unit can be calculated in the final step. Equation 2 shows how these are calculated.

$$Costs\ per\ m = \frac{Investment\ costs + (Operating\ costs/hour * 24h * production\ days)}{Production\ output} \quad (2)$$

For the application in electrode production, 1 unit is seen here as 1 m of electrode foil produced. The result now provides a classification of the solution with regard to the degree of automation, flexibility level, and costs. In order to be able to better compare the individually evaluated solutions, a utility analysis [25] with the two criteria cost and flexibility can be done. The weighting between the criteria must be defined depending on the use case. Furthermore, an evaluation scale of 1-6 was chosen. For the evaluation of flexibility, 100% was evaluated with a 1 as the best result. For costs, the scenario with the highest cost per m was rated with a 6 as the worst result, and the costs of the other scenarios were derived based on this. This can be done according to different observation periods. Thus, depending on the weighting, it can be seen how the solutions behave depending on the observation period.

4.2. Evaluation of three scenarios

For the exemplary application of the method in electrode production, three different scenarios were defined. Each scenario is characterized by the logistics systems for the logistics processes described in Chapter 2.2. Further, realistic values for production parameters and a cost basis were set.

Table 5 shows the basis of the three evaluated scenarios. Scenario 1 is a fully automated solution in which no workers are required for logistics activities. An automated conveyor belt has been chosen as the means of transport. Stationary robots are used for handling and packaging tasks. As can be seen in Table 4, flexibility is therefore only rated as 1 in some places. Scenario 2 continues to use the automated solution for the packaging and handling tasks, but manual electric forklifts are used for transport tasks. Scenario 3 is a purely manual solution with increased personnel requirements. In addition to manually operated electric forklifts, manually operated handling and packaging equipment is used.

Table 5. Input parameters of the three evaluated scenarios.

Input	**S1**	**S2**	**S3**
Production			
Production output [km/observation period]	6,912 - 103,680	6,912 - 103,680	6,912 - 103,680
Production speed m/min	80	80	80
Shift schedule [Shift/day]	3	3	3
Logistic processes which can be automated	82	82	82
Observation period [days]	60 to 900	60 to 900	60 to 900
Automation			
Number of automated logistic processes	82	52	0
Number of automated units for transport; handling; packaging	1; 28;10	28; 28; 10	0; 0; 0
Number of manual units for transport; handling; packaging	0; 0; 0	10; 0; 0	12; 28; 10
Number of workers	0	5	12
Flexibility			
Quantity flexibility Q_f Q_1; Q_2; Q_3; Q_4 ; Q_5 ; Q_6 ; Q_7	1; 1; 1; 1; 1; 1; 1	2; 2; 2; 1; 1; 1; 1	2; 2; 2; 2; 2; 2; 2
Material flow flexibility M_f M_1; M_2	1; 1	2; 2	2; 2
Variation flexibility V_f V_1; V_2; V_3; V_4; V_5; V_6; V_7	1; 1; 1; 1; 1; 1; 1	2; 2; 2; 1; 1; 1; 1	2; 2; 2; 2; 2; 2; 2
Cost			
Investment costs per transport resource automated			130 T€
Investment costs per handling resource automated			70 T€
Investment costs per packaging resource automated			70 T€
Investment costs per transport resource manual			15 T€
Investment costs per handling resource manual			10 T€
Investment costs per packaging resource automated			10 T€
Operating costs per worker (Clean-/Dry room usage)			22.8 €
Operating costs per transport equipment automated			50 €
Operating costs per handling equipment automated			50 €
Operating costs per packaging equipment automated			50 €
Operating costs per transport equipment manual			40 €
Operating costs - Handling equipment - manual			40 €
Operating costs – Packaging equipment - automated			40 €

In the first evaluation without the goal of flexibility, the observation period was chosen with an interval of 20 days, starting with 60 days, to analyze the production time, after which the fully automated variant in Scenario 1 leads to lower costs per meter despite much higher investment costs.

Table 6 shows the evaluation of the three scenarios.

Table 6. Evaluation of the three scenarios.

Evaluation	**Scenario 1**	**Scenario 2**	**Scenario 3**
Automation level	100%	63%	0%
Flexibility level	50%	75%	100%
Investment costs [€]	2,790,000	2,810,000	530,000
Operating costs [€/hour]	1,950	2,414	2,194
Costs per unit [€/m]	0.81 - 0.43	0.91 - 0.53	0.55 - 0.48

The investment costs for Scenario 1 and Scenario 2 are significantly higher than those of the manual variant (Scenario 3), but the operating costs are lower, which can be related to employee demand and the resulting costs. Furthermore, Fig 2 shows the costs per m as a function of the production time.

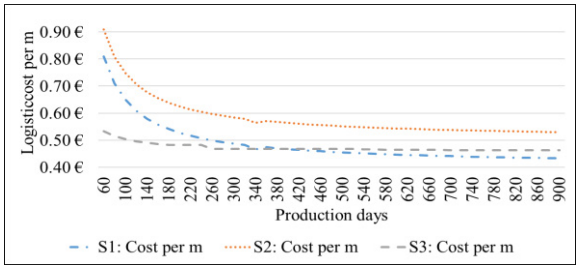

Fig. 2. Logistics costs in meters as a function of production time.

After 420 days, the costs in Scenario 1 are lower than in Scenario 3 at 46 cents per m. Scenario 2, on the other hand, has the highest logistics costs per m consistently. The analysis shows that a consideration of the cost development

over a longer period of time is indispensable. The last step is to merge the flexibility target with the cost calculation. In a utility analysis [25], both goals were compared together in one value. The rating scale was defined as 1-6, with 1 being the best. Scenario 3 receives a 1, as the degree of flexibility is 100%, and Scenario 1 receives a rating of 3. In the evaluation of the costs, the highest costs for the respective production period under consideration were given a 6. The cost evaluation of the other scenarios was determined accordingly. In the evaluation, a weighting of 50/50 and a weighting of 90% for costs and 10% for flexibility was initially determined, and it was observed, after which production time a 90/10 evaluation would lead to Scenario 1 performing better. Furthermore, it was evaluated how the scenarios behaved after an observation period of 1920 days. This would represent eight years, which is a typical depreciation period for machines. Here, the weighting at which Scenario 1 performs better was examined. The results can be seen in Table 7. A comparison is to be read only per line, and the lowest value of each target performs best.

Table 7. Results of the utility analysis.

Prod. days	Weight (Cost/Flexibility)	Scenario 1	Scenario 2	Scenario 3
20	90/10	538.60	565.00	**236.05**
	50/50	432.56	425.00	**175.58**
420	90/10	476.55	565.00	**459.53**
	50/50	398.08	425.00	**299.74**
640	90/10	**473.25**	565.00	473.31
	50/50	396.25	425.00	**307.39**
1920	80/20	449.93	530.00	**447.66**
	81/19	**451.80**	533.50	452.01

Scenario 3 mostly performs best. Scenario 1 performs better with a weighting of 90% for costs after 640 days and with a weighting of 81% for costs after 1920 days. Compared with the evaluation purely on the basis of costs, the break-even point was already reached after 420 days. It shows that for a decision, the objectives must be considered in combination, and the weighting has a further impact on the decision.

5. Conclusion and Outlook

The battery cell industry is a rapidly growing market. At the same time, the need for flexible and efficient production is important. The design of logistics as a connecting component can play an important role here. Automated systems can be an approach to reduce the number of employees and to produce efficiently at the same time. The developed method offers the possibility to compare different logistics systems regarding automation, flexibility, and economic efficiency. The three selected scenarios further show that a consideration of the solutions over a longer period of time is also relevant. Automated solutions are often significantly higher in terms of investment and only amortize after a period of time. At the same time, they are often less flexible. The method presented in this paper offers a possibility to evaluate this target criterion as well.

Since empirical values were used for the cost basis and assumptions were made for the input parameters, further work could break down the cost basis and concretize it for logistics systems. Additionally, a uniform interface for the considered facilities for electrode production and the logistic systems can be developed to simplify the planning. The evaluation of the scenarios can also be extended in a further study. For example, a simulation approach could evaluate further criteria, such as the utilization of the logistic resources. In addition, the method itself can be further developed, and, for example, a cost-only comparison of solutions can be made by performing an in-depth analysis of the impact of lack of flexibility on costs.

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