An approach for the identification of production process variables in cross-process chain production processes like battery cell production

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Abstract: Europe is currently not competitive in battery cell production. In order to increase competitiveness, battery cell production must be made more efficient. A major factor in improving efficiency is the reduction of waste. This requires understanding the many dependencies between the production process variables within battery cell manufacturing. For clarifying these dependencies, knowledge of the variables is essential. The challenge here is to completely determine them. For this purpose, different tools and methods are applied. But, in the case of cross-process chain production processes like battery cell production, they quickly reach their limits because these tools are not suitable for the structure and properties of the respective processes. The aim of the approach presented here is to support a complete identification of all process variables of battery cell production in the best possible way.

Keywords: Battery cell production, Identification of process variables, Cross-process chain production processes.

1. Introduction
Lithium-ion batteries have established themselves as a key technology for the electrification and hybridisation of drives in a wide range of application areas due to their power and energy density [1, 2]. For the quality of the lithium-ion cell, the manufacturing process of the cell as well as the materials used for production are crucial [3]. In addition, costs must be reduced for competitive battery cell production. For this, inefficiencies such as rejects or increased material consumption must be reduced [4]. By monitoring the production processes the quality targets and the cost reduction can be achieved [3].

1.1. Research issue
For monitoring the production processes it is elementary to know the key variables of it. Therefore a fundamental understanding of the diverse dependencies between the various parameters within battery cell production is necessary. These dependencies are also called influence-cause-effect relationships and describe the effect of influencing variables on the target variables [5]. For battery cell production, however, these relationships are not fully known and cannot be easily derived [6].

A particular challenge lies in the characteristics of battery cell manufacturing itself: A large number of interlinked process steps, coupled with different types of manufacturing processes (e.g. process
engineering, mechanical processing, assembly) [7]. The interlinking of process steps means that previously insignificant process parameters and complex cause-and-effect relationships over several manufacturing processes lead to defects and deviations in the manufactured products. The causes for these deviations can therefore not only find in the corresponding process steps, but already in the upstream processes [8]. Therefore, a comparatively simple improvement of the individual process cannot eliminate the cause and the complete production process cannot be optimised. Therefore, the focus should be on the entire process chain in order to increase quality [9]. However, with a complete view of the process chain, the number of parameters and the influence-cause-effect relationships increase significantly compared to the individual processes [8]. In addition, the traditional methods of quality management are often focus on the examination of individual processes. They quickly reach their limits when it comes to cross-process chain processes [10].

1.2. Objectives and tasks

Some research efforts, increasingly in the recent past, have addressed the description of cause-effect relationships and have identified relevant process variables or optimised the manufacturing process of battery cell production [11–15]. With the exception of Westermeier [16] none of the approaches describes, how the process variables under consideration become part of the scope of the study. The basis there is presumably an already available selection of process variables, which are recorded by data technology and used for the mostly data-driven approaches. The disadvantage of these data-driven approaches is that only those process variables can be included that are also recorded using data technology. This is probably less critical for the target variables of production processes, also called output variables. These correspond to the characteristics of the product to be manufactured. The characteristics are specified in drawings, specifications, catalogues, etc. and are therefore known. In contrast, influencing variables are not explicitly specified, individual variables may even be unknown and not integrated into the data-driven approaches. This may lead to incorrect interpretations of the cause-effect relationships. As a consequence it makes it impossible to achieve the quality goals and reduce the costs [17].

In order to improve the quality and to avoid forgetting influencing variables, the goal of this approach is to develop a method that supports the identification of influencing variables. Therefore, this paper covers the manufacturing process of the battery cell production, the tools and methods, which are used for the determination of influencing variables in cross-process chain production processes. The criteria for the new method are defined based on the above-mentioned production processes and the already known tools and methods. The method is developed to meet the defined criteria specific to battery cell production.

2. State of the Art

In order to improve quality, various methods and tools are used to identify influencing variables in the field of quality management [18]. Influencing variables include input, control, disturbance and state variables. Due to the specialities of cross-process chain production processes like battery cell production, output variables within the process chain also count as influencing variables, since output variables from previous processes form input variables in follow-up processes [19]. In order to obtain an overview about the dependencies between the processes of the battery cell production, these is specified in the following section, followed by the existing tools and methods to identify the above-mentioned influencing variables.

2.1. Manufacturing Process of a battery cell

The manufacturing process of the lithium-ion battery cell is divided into three main process steps: electrode production, cell assembly and cell finishing [20]. In electrode production, the active materials, binders and additives with organic solvents are first mixed to form a so-called slurry. Then the anode and cathode foils are coated, dried and calendered to get a homogenous layer thickness [21]. The next step after the electrode production is the cell assembly. The cell assembly depends on the type of the
cell: the pouch cell, the prismatic and the cylindrical cell. For the pouch cell the anode, cathode and the separator are stacked [20]. For the prismatic and the cylindrical cell the anode, the cathode and the separator are wrapped [22] and the prismatic and the round cell, the so-called Jelly Roll, is fixed with adhesive tape [23, 24]. During packaging, the cell is placed in a housing [25]. After that the electrolyte is filled. The electrolyte soaks the separator and wets the electrodes [26]. The first step of the cell finishing is the forming of the cells. During this process, the cells are charged for the first time and the solid electrolyte interface (SEI) layer is created [25]. During the maturation of the cells, the cell performance and the properties of the cell are monitored over a certain period of time. Finally, the cells are checked regarding their functionality during the end-of-line test [7].

2.2. Tools and Methods

2.2.1. One-dimensional tools. In order to determine the influencing factors of the respective product features, brainstorming is generally used [17, 27]. Brainstorming is a technique for generating ideas. It is intended to stimulate the creative thinking of a team [17]. This is supported by various tools which will be explained briefly below.

The best-known tool to support brainstorming by identifying influencing factors is the Ishikawa diagram. Another term is the cause-effect diagram. This tool graphically illustrates the relationship between an event and all factors that influence it in a structured way. This form resembles the bones of a fish in an abstract form and is therefore also called a "fishbone" diagram [28]. In the present application, the result is a product characteristic produced by the production process. The factors are influencing the product characteristic. Five categories are used to better structure the influencing factors: man, machine, material, method and environment. The recorded influencing factors are also known as general factors and can be divided down to the basic factors [29].

A further support is provided by the process flow chart: the subdivision of the production process into individual steps is followed by a description of the procedure and the input and output factors [17]. The identification of factors can additionally be supported by a Failure Mode and Effects Analysis (FMEA) [30]. The actual field of application of FMEA is the preventive risk analysis in the investigation of products and processes [28]. By using the FMEA to analyse causes, it is also suitable for identifying possible influencing factors of a process [31] and has been used for identification of variables in battery cell production as well [32].

2.2.2. Multidimensional methods. While the tools have their focus on individual processes, the multidimensional methods presented below focus on the cross-process chain view which is necessary for battery cell production. Due to the limited extent of the paper, only the respective partial aspects of the approaches that concern identification will be presented.

Jung subdivides in his approach the complex processes with the top-down subdivision into main, secondary, sub-processes and activities. He also differentiates the variables involved in the process into input and output data as well as into influencing and disturbance variables. In addition to a forward view of the processes, there is also a backward view of the process chain to visualise further interrelationships [33].

Eichgrün and Schäfer limit the view by the start and end points of the process chain. In Eichgrün's process model and Schäfer's structural modelling, a clear distinction is made between input, output and state variables. Eichgrün examines feature changes on the workpiece with regard to the dimension's geometry, surface, edge zone and workpiece core, so that different perspectives are generated. By considering the feedback of the output variables to the next process step, Eichgrün takes a cross-process chain view. Similarly, in Schäfer's behavioural modelling, there is a graphical forward- and backward-coupled modelling from the influencing variables via the processes to the manufacturing characteristics. Eichgrün's structural model subdivides the process chain hierarchically into the process unit, the main and secondary processes as well as the sub-processes and the activities and visualises these with the intermediate states. This subdivision is also used by Schäfer [8, 9].
Hielscher models the structure of the process chains by breaking down the process units into main and secondary processes. After the subdivision of the process units, the boundaries of the consideration are defined. Subsequently, the input, state and output variables are considered in the fine modelling for the main and secondary processes [10].

In Westermeier's description model, all necessary so-called system elements of the process chain are recorded at the beginning through a survey of experts. These elements are classified into quality characteristics, processes, sequence of processes, intermediate states and intermediate product structure. System elements additionally include intermediate product characteristics, process and machine parameters, time-dependent state variables, environmental conditions, possible disturbance variables as well as input products and input product characteristics [16].

3. Results
In order to develop a method that is suitable for the identification of influencing variables in cross-process chain production processes like battery cell production, corresponding requirements must be defined. For this reason, the current chapter first determines the requirements. Then the developed method is discussed and the reference to the requirements is established.

3.1. Determined requirements
From the characteristics of battery cell production presented in advance and the positive aspects of the approaches presented in section 2.2, requirements for the method to be developed can be derived. For cross-process chain production processes, as illustrated here using the example of battery cell production, seven requirements result.

As already mentioned, a complete identification of all influencing variables is necessary for the determination of cause-and-effect relationships in the battery cell production. Therefore, completeness is the first requirement. The generation of different perspectives plays a decisive role. Therefore, the forward as well as the backward view of the manufacturing processes, the intermediate products and the influencing variables is necessary. The change of the viewpoint enables new perspectives and provides a better overview of the process. By using different views previously unknown and insignificant influencing variables can be identified. A large number of involved people also leads to new perspectives.

In addition to completeness, complexity is another requirement. The more complex the tools and methods, the higher the risk for occurring errors during the process and the issue that not all necessary steps are considered. As a result, the cross-process chain processes and the influencing variables are not taken into account in their entirety. The knowledge required to use the tool or method is derived as a subordinate requirement. If a high level of knowledge of the users is required, the higher the risk of a lack of acceptance.

Another requirement is the applicability to the high number of processes, the intermediate states and the influencing variables which characterises battery cell production. The manufacturing process of lithium-ion batteries exist of three processes with more than twenty main processes. Therefore, it must be possible to take all processes into account in order to identify influencing variables. For this purpose, design for a large number of processes is selected as a partial requirement.

Practicability also plays an important role. Therefore, the cross-process chain consideration of the large number of processes, the intermediate products and the influencing variables is relevant. The requirement cross-process chain consideration of the processes is added in order to evaluate the complete recording of all processes, the main processes, the secondary processes, the sub-processes and the activities along the entire process chain.

Reproducibility is another overarching requirement. A transparent procedure and presentation should ensure that people who were not involved in the identification of the influencing factors can understand the determination. For the reproducibility, a classification and visualisation of the influencing variables in the field of battery cell production is necessary in order to distinguish them from each other. This
generates a uniform understanding of the processes, the intermediate products and the influencing variables in order to avoid misunderstandings.

In addition, visualisation plays a decisive role in the identification of influencing variables. This does not only increase the clarity of a large number of processes and influencing variables, but also enables increased creativity. Therefore, the graphical visualisation of all the battery cell manufacturing processes should be mentioned as a subordinate requirement. This leads to a better awareness of the overall process and prevents individual processes from being ignored.

The final requirement is the transferability. This is because the tool or method should not only be able to be used for cross-process-chain production processes in the area of battery cell production, but also for other cross-process-chain production processes in other areas. Therefore, the suitability for other processes plays a significant role.

3.2. Developed approach
Based on the determined requirements in the previous sector the new method is developed. The concept of the method is based on the generation of tacit knowledge and the application of the tacit knowledge in explicit form supported by an Excel-based tool (see figure 1) and is explained in the following sections. Based on the definitions, explicit knowledge is defined as written knowledge, while tacit knowledge is referred to as experiential knowledge [34].

**Figure 1.** Procedure for the identification of the influencing variables.

3.2.1. Generation of new tacit knowledge. First of all, the generation of tacit knowledge needs to take place. The tacit knowledge is generated by the existing written knowledge and by the experiential knowledge of the employees. Explicit knowledge is already available by designing the product and the process. Through the Process-FMEA, the work plan, the control plan and the test plan, information about the processes and the influencing variables are available in explicit form. But first of all, the documents described above must be examined with regard to possible information for identification (including process steps, already documented influencing variables, weak points of the process). In addition, the employees involved in product and process creation already possess tacit knowledge due to many years of experience. Individual employees from different areas (e.g., development, production planning, production, quality) or from departments with similar manufacturing processes can be considered in a proactive exchange of information. Through the exchange between the different actors with different
3.2.2. Application of tacit knowledge and generation of explicit knowledge. Through the identification of influencing variables in a workshop format, the newly gained tacit knowledge is applied to document the knowledge and make it explicitly available. The implementation of the knowledge transformation is done with an Excel-based tool. The Excel file is split in three different sheets. Each sheet represents a processing step of the method.

**Figure 2.** Graphical representation of the process chain and determination of the influencing variables.

**Step 1:** Graphical representation of the process chain
First of all, a graphical representation of the process chain takes place in sheet "1". The process chain with the individual processes is modelled horizontally and the processes are listed vertically with the production equipment (see figure 2). First the processes with the equipment and then the main processes with the machines are modelled horizontally and finally listed vertically in a table. For each main process, a new sheet is generated in which the associated secondary processes with the machines as well as the sub-processes with the tools and the activities with the auxiliaries can be added. Through the complete determination, all processes can be included in the subsequent identification of the influencing variables. In order to generate different perspectives, a forward and backward, as well as a top-down and a bottom-up view of the processes also takes place to generate new perspectives and to make sure all processes are taken into consideration while determining the influencing variables along the whole process chain.

**Step 2:** Graphical representation of the processes and their influencing variables
Subsequently, in the graphical representation of the main process in sheet 2, the intermediate products before and after each main process are determined for the main process. To support the determination of the intermediate products, the previous and following processes can be selected in the Excel tool so that the subordinate processes appear with the production equipment and the process is shown in visible way. The relevant influencing variables for the process are then determined. For this purpose, the input and output variables are first added, taking into account the individual processes and the intermediate products. In addition, the control, disturbance and state variables are determined for...
this main process. Then, taking into account the output variables of the previous process, the input variables of the considered process are identified. By considering the end product of the process the output variables are identified. Taking into account the change of the intermediate product as well as the control, disturbance and state variables from the previous process, the control, disturbance and state variables for the considered process can also be determined. Finally, the main processes with the defined influencing variables can be compared and missing influencing variables can be added. This process is shown in figure 2.

Step 3: Graphical representation of the influencing variables per main process

In sheet 3, the influencing variables are automatically displayed in a matrix with the assignment to the main processes. The influencing variables are listed vertically and are assigned horizontally to the process step as the defined influencing variable. This makes it possible to show the influence variables while they have been determined several times to different processes. Furthermore, the determined influencing variables can be checked for spelling errors and thus similar multiple entries can be avoided.

3.2.3. Results. Using the above-mentioned method for the identification of the influencing variables with the Excel-based tool for the battery cell production a large number of processes, intermediate products and influencing variables can be determined. The process chain is split in three processes and more than twenty main processes. For every main process at least two secondary processes, two to six subprocesses and four activities are identified. The number of influencing variables, which are determined for every main process, is between five to twenty influencing variables. Around ten till twenty input and output variables with around five to twelve control, disturbance and state variables are entered in the tool. As a result, more than 500 influencing variables could be determined with the above-mentioned method and tool.

4. Conclusion and outlook

In the context of this paper, a concept was presented to identify influencing variables in cross-process chain production processes using the example of battery cell production. The method with the presented tool is based on the generation of tacit knowledge, the application of tacit knowledge and the generation of explicit knowledge. This was already applied in the context of the identification of influencing variables in the field of battery cell production. In addition, many influencing variables were identified and recorded. In order to verify this further, a comparison should be made in the future with other research work on this topic to see whether a similar number of influencing variables have been identified or not. On the other hand, successful proof of the cause-effect relationships can confirm whether all influencing variables have been identified. For this, however, further steps must be taken first, such as the selection of suitable measurement sensors for recording the influencing variables.

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