# Conception of Technology Chains in Battery Production

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**Abstract.** Mainly activated by the ambitious global political targets in terms of electrification of transport, the demand for lithium-ion cells will rise strongly in the coming years. Currently, the request is slowed down by the high prices of battery cells. The production process of battery cells is characterized by very heterogeneous areas of expertise in the various process steps. This complicates the economic design of the whole production process considerably and leads to a focusing of the plant engineers to their original core issues. Therefore this article engages at this point and provides a methodology to support the production planner along the entire production planning process. After defining the requirements for the production line, the singular performance of technological alternatives, their suitability for the product as well as the interplay of alternatives are checked. Within in the focus of this paper, all steps are shown in context to lithium-ion-cells. Nevertheless, the presented methodology has a generic approach and can therefore also been used for other production processes.

## 1 Introduction and motivation

In august 2007 the European Union published a postulation on cutting down about 40% on $CO_2$ emissions in comparison to the year 1990. In Germany, this demand initiated the "Nationaler Entwicklungsplan Elektromobilität" (National Development Plan for Electric Mobility) in the year 2009. This plan includes the ambitious goal to get one million electric vehicles on the streets in 2020. Although the goal currently has been reduced to about 600.000 vehicles, the demand for Lithium-Ion-Cells will rise in the next years. However, not only Germany is a driving force for this trend. Also the Chinese government pursues ambitious plans by claiming that up to 500.000 hybrid and pure electric vehicles will drive in China in the year 2015. In 2020 there shall be a vast production volume of about 5 million vehicles per year. Today the predicted growth is slowed down by the complex and disruptive technology change from internal combustion engines to electric engines as well as by the high prices of electric vehicles. The battery is a significant factor of the pricing, concerning that 60% of the production costs and 40% of the overall costs can be tracked down to the battery. Regarding very low priced vehicles these figures can rise, so that the battery costs outrun the value of the residual vehicle. Comparing the worldwide goals and potentials with the cost structure of electric vehicles, it is obvious that a reduction of costs is indispensable. A potential approach for reducing costs in battery production is the reduction of the costs of production by a more structured conception of the technology chain. An internal study of the Laboratory for Machine Tools and Production Engineering points out that only a few of more than 200 national and international machine and plant engineering companies are able to cover several process steps due to their competences. In fact a plurality of specialists serve the value added chain of the cell production. By doing so, they apply their competences in a partial process on the battery production. The operator of a lithium-ion-cell production is challenged by the identification of national and international machine and plant engineering companies for every process step. He has to instruct these specialists, which production technology has to be used, and connect all machines and plants to an economic overall process. There has to be a methodology conceived in order to support this decision-making process and systematically design technology chains. This would lead to more balanced investments over the different process steps and so reduce the overall costs.

To present this approach, the article is structured as follows. First, the existing approaches and their weaknesses are discussed. This is followed by the presentation of the structure of our new methodology. Based on this, we show how the methodology was used at our institute. The article ends with a conclusion.

## 2 Existing approaches

The evaluation of the existing approaches and their weaknesses, as follows, is based on a set of criteria. The approach generates one or more technology chains out of a set of previous identified technologies (criteria 1). This should include assembly processes (criteria 2). Based on the identified production technologies, production resources can be assigned to them (criteria 3). The interactions and influences between technologies and production resources have to be taken into account, in order to guarantee an optimal adjustment. Not only interactions between neighbored, but between all technologies and production resources should be considered (criteria 4). A cross-company consideration of technologies and production resources is important as well (criteria 5). In order to guarantee global competitive and economic technology chains, an evaluation of the technology chains is important. THADEN states that, time, costs and quality are especially relevant for process performance evaluation. [1] SCHUH sees the degree of maturity of a technology significant for the technological-strategic success of a company. [2] In addition flexibility should be taken into account (criteria 6).

FALLBÖHMER`s approach does not consider interactions and influences between all technologies. His approach only considers neighbored technologies. The focus of FALLBÖHMER`s approach is on production technologies only, production resources are being left out. [3] Assembly processes are not discussed, as well. The approach P.A.R.T. developed by VAN HOUTEN states, that work steps create conditions by which the following step is measured. The consideration of the influences on not neighbored technologies is being left out, as well as assembly processes and cross-company consideration. VAN HOUTEN focusses only on machining. [4] The identification of disruptive technologies is the focus of KOSTOFF`s approach. [5] The generation of a technology chain is not discussed. The approach leaves out interactions and influences between not neighbored technologies.

## 3 Structure of the method

The methodology consists of four main steps. The first one defines the requirements with regard to the product and the process. Then the general performance of technological alternatives for the different process steps gets determined. In the last step before the final conception, the suitability for the product as well as the interplay of the alternatives is checked. All these information are represented through three, so-called, technology values which show how high the performance of one alternative is for the certain case. At least these values were aggregated to an overall technology value. This rate determines than the final choice of the technologies.

### 3.1 Definition of the product and process characteristics

At the beginning, all favored product and process characteristics are specified. Then the technology chain gets designed with this information. The phase is divided in to three steps. First, the product characteristics are defined and then recorded in a product profile. Afterwards a process profile is defined, which is used to create an ideal profile including all requirements on the production technologies.

In order to ascertain the favored product characteristics, all customer requirements relevant to the application and their influences on the product characteristics have to be defined. Thereto the correlation matrix is used (cp. Fig. 1). The product characteristics are arranged in groups on the horizontal axis. The vertical axis on the left side represents the relevant costumer requirements derived from the product specification sheets. They are completed with two additional columns. In the first column, the target course of a characteristic is displayed by arrows. The second column is used to consider the diverging relevance of different costumer requirements due to a variable weighting. In dependence on the QFD-process-matrices this weighting is multiplied with the strength of the correlations and a higher sum results for every single product characteristic. Every field in the matrix represents the relation between a costumer requirement and a product characteristic. Two pieces of information can be recorded. At first, this is the strength of the relation, illustrated by the "House of Quality"-symbolism and their numerical value, considering a weak relation with one point, a medium relation with three points and a strong relation with nine. The correlation matrix distinguishes from the "House of Quality" by the second information, which can be recorded in every field. That is what the target course is. The target course can be distinct in the form minimize, maximize or specify and shows how a specific product characteristic can clearly fulfill the customer requirements. After recording all information, the weighting can be used to specify on which product characteristic the operator has to focus on, in order to fulfill the customer requirements as much as possible. Therefore, the product profile is created by assigning a weighting to every product characteristic. For example, it is not directly apparent how a costumer requirement for a high performance cell influences the production process. However, the correlation matrix shows that this type of cell requires a low coating thickness. This parameter can easily be matched with the performance characteristics of a production machine. (cp. Fig. 1)

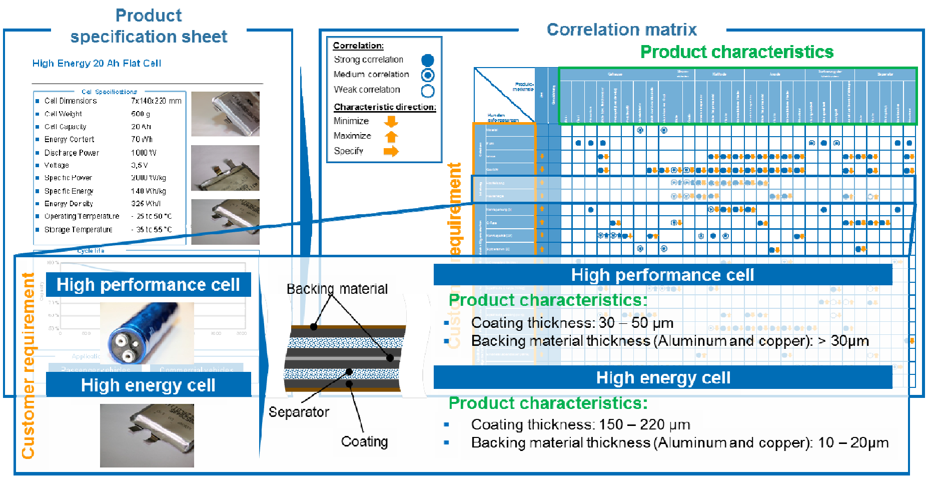


**Fig. 1.** Definition of the product characteristics

Subsequent the process profile is defined. Thereto the crucial characteristics have to be defined. The most important process characteristics are maturity, flexibility, costs, time and quality according to the relevant literature of KLOCKE, THADEN and BECKER.

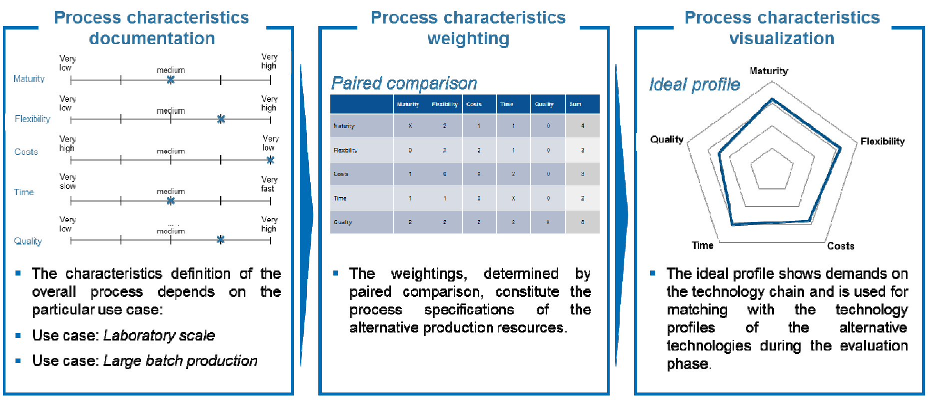


**Fig. 2.** Definition of the overall process characteristics

In order to these process characteristics all possible specifications are defined. Due to conflicts of goals between the different dimensions, the use of a paired comparison is recommended. The methodology operator can ponder which process characteristic is the most important to him. For the generation of the ideal profile it is necessary to normalize the sum to a value of five. It has to be mentioned that the values more outside represent a better performance. Later this profile is being used to match the customer's ideas with the performance of the production resource's.

### 3.2 Identification and evaluation of production resources

After defining the requirements of the operator in the correlation matrix (product) and the ideal profile (process) in the first phase, the attention is now on the production process. Thereto the steps "value added chain conception" and afterwards "identification and evaluation of technological alternatives" are necessary.

In the methodology two procedures can be used for the designing of the value added chain. KLOCKE states, that a technology chain is a combination of production processes in a defined order to produce a product. In doing so, every production process's task is to create or change one or more product characteristic. After each production process the work piece of the product can be stated in an intermediate stage. The focus on those intermediate stages is very important for the generation of the value added chains, as interfaces between the processes can be depicted. The initial state, produced by a technology *n*, has to match with an input state, produced by technology *n+1*. This procedure enables a continuous process. When the states are defined, the production technologies for each step have to be chosen. [6] Based on the analysis of known technology chains, there are four classes of technologies: the shaping, form changing, feature changing and joining technology. They can be sorted in to classes orientated to the DIN8580 [7].

FALLBÖHMER's methodology states an alternative approach. His methodology is based on a strong informational connection between product and technology. During the product's rough planning and the ascertainment of the functional product features, the designing engineer confers with the technology planer. Just after comparing the product requirements with the production resource's potentials, the detailed planning starts and non-functional product features are being designed. [8] Both procedures enable the operator to design the value added chain with a minimal effort due to a systematical approach. This is the basis for the identification of alternative production processes along the entire process chain. [9]

Based on the designed value added chain, alternative production processes have to be identified. Therefor the technology monitoring developed by SCHUH is used. [10] In case of the production of a Lithium-Ion-Cell it has been executed for every process step. Overall 128 alternatives from mixing to the final quality check have been identified. The gathered information has been recorded in the morphological box (cp. fig. 4. left side).

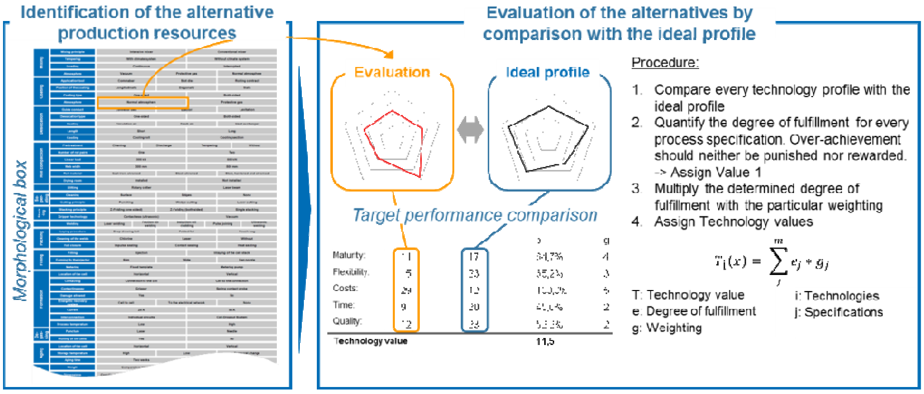


**Fig. 3.** Identification and evaluation of the production resources

Now, the technology evaluation is used to evaluate the identified alternatives based on a plurality of criteria and match them with the ideal profile. The highest technology value is assigned to the alternative technology with the best match to the ideal profile. The criteria are formed by the process characteristics maturity, flexibility, costs, time and quality again. Each criteria itself contains sub-criteria. The singular technology evaluations are summarized based on the process characteristics, in radar charts. The axes of that radar chart are formed by the five process characteristics. The first technology value, used for the selection of the production resources, is calculated with this data and the formula shown in Fig. 4. on the right side.

### 3.3 Identification of interdependences

In the next step, the focus moves from unique technologies to their connections with the product and with other production resources. These two poles are processed successively. Each area of tension delivers one further technology value.

The connections between technologies and product properties are shown in the technology map. All investigated technology variants noticed in the morphological box are entered into this map and ordered according to their appearance in the value chain.

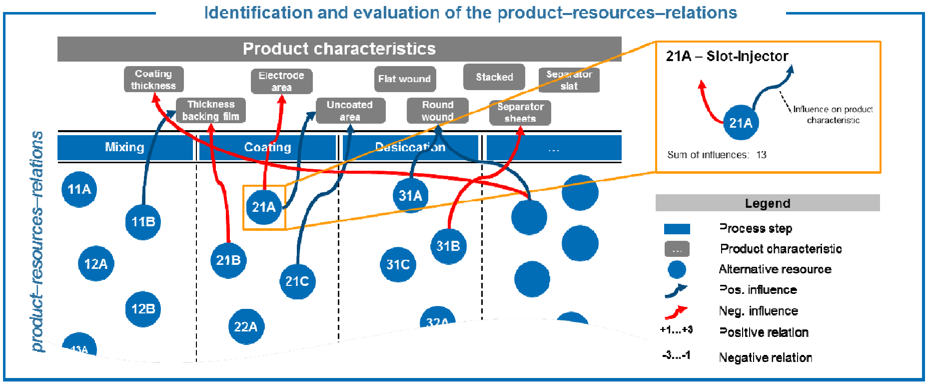


**Fig. 4.** Identification of product interdependences

Technology variants, which can be used in the first production step, are entered into the first column, technology variants, which can be used in the second production step, are entered into the second column and so on. In this way, all technology alternatives noticed in the morphological box are entered into the map. Afterwards, the identified technology properties are filled into the row above the different process steps. Finally, the connections between technology and product are drawn in as arrows. They start at the technologies (drawn as circles) and end at the product properties (drawn as grey rectangles). Positive connections are drawn in blue and negative in red. Each arrow possesses an edge weight which is divided into three classes (weak – 1, medium – 2, strong – 3). Positive and negative connections are differentiated by the sign. For those connections two examples between product properties and production alternatives are presented below:

- High coating thickness on cathode side – Application tool slot die
  *Quality +3:* There is no risk of contact between the die and the surface of substrate. The process stability is guaranteed. The greater material flow is adjustable by the pump settings. Although the die chamber and the exit slot can be designed for a greater material flow.
- Enclosure made of aluminum foil – Filling under vacuum
  *Quality +3:* In order to the elastic properties, the pouch cell puffs out under vacuum conditions. After raising the pressure, the cell has its starting volume. Through the constant change of pressure it comes to the suction effect. The suction effect improves the inclusion of electrolyte in a strong way.

The technology map is primarily used for the visualization and comprehension of the search results. After the completion of the technology map, the identified connections between technology and product are calculated by using the impact matrix. The impact matrix is an n x m-Matrix (n technologies, m properties). The technologies are entered into the rows and the properties into the columns. The user has to fill out the matrix with the intensities of the connections (including signs). These intensities have to be evaluated and added up to the sum of influence. Through scaling (value between one and five) the sum of influence, the second technology value is generated.

After evaluating the suitability of the technologies with regard to the product, the suitability of the different technologies has to be evaluated. Problems at the several process interfaces and with the designing of production facilities should be minimized. Therefore, the technology interdependencies have to be visualized by entering these interdependencies into the so-called technology map. The technology map includes all technological variants. Alternative technologies are entered among each other and technologies, which follow one another in the value chain, are entered next to each other. Technologies are drawn as circles and interdependencies are drawn as arrows. An arrow between technology A and technology B means, that A has an influence on B. The intensities of the interdependencies are characterized by values at the arrowheads. -1, -2, -3 (with increasing intensity) are used for negative interdependencies and +1, +2, +3 (with increasing intensity) are used for positive interdependencies. To facilitate an understanding of the different interdependencies two examples are listed below:

- Slitting with laser cutting – Separation with laser cutting
  *Time +3:* The use of laser cutting during the slitting process allows the determination of a final edge, so that the second laser must only finalize three edges in the separation process. This procedure saves time.
- Conventional mixer – Coating knife
  *Quality -1:* The conventional mixer tends to build agglomerates which are, in case of the use of a coating knife, especially dangerous for the quality of the coating. The reason is that they get stuck between the knife and surface of the ground material which influences the material flow permanently and leads to strips in the coating.

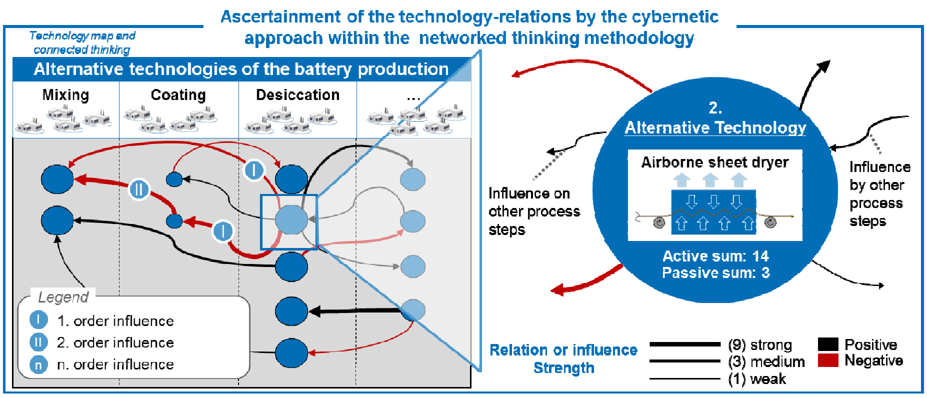


**Fig. 5.** Identification of interdependences 2

After the visualization of the interdependencies by using the technology map, the interdependencies are entered into the so-called impact matrix. These data are evaluated by the help of the methods of networked thinking [11] and generate a further technology value. The evaluation of the technological interdependencies is carried out separately for each process property (costs, quality, flexibility …) and generates different subtotals. Taking account to the weights of the properties, these subtotals generate the last technology value.

### 3.4 Selection of production technologies

The final stage of technology chain development is the linking of the evaluated technology variants and the creation of a production technology chain, which fulfills the specifications of the product and process profile. Therefore, the generated technology values are combined to one value. With regard to the properties of the technology chain, preferences are defined. Depending on the preferences, the generated technology values influence this value differently. These preferences are defined at macro-level, while the preferences mentioned in the previous chapter are defined at micro-level. The technology schedule helps to decide, which aspects of technology are more important than others. Therefore, these different technology chains can be selected:

- Normal technology chain
- High-performance technology chain
- Customer-oriented technology chain
- Homogeneous technology chain
- Individual technology chain

The normal technology chain assesses the three components of technology evaluation equally. With regard to the final evaluation value, the three generated technology values have the same influence-coefficient (performance-factor). If there are special preferences, one of the other technology chains should be chosen. (cp. Fig. 7)

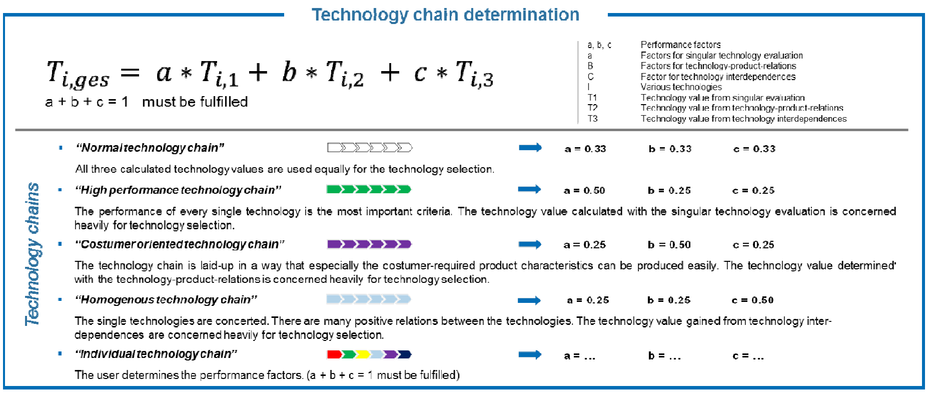


**Fig. 6.** Types of technology chains

After choosing the type of technology chain, the final technology value has to be generated for each technology alternative. With regard to the considered process step, the technology alternative with the highest value has to be chosen. If several alternatives have the same value, the adjacent process steps and possible complications also have to be inspected.

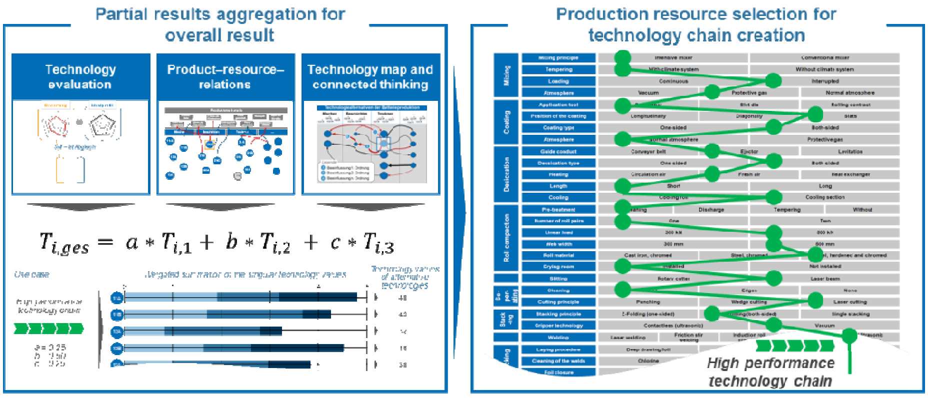


**Fig. 7.** Selection of production resources

## 4 Case study

For the scientific verification of this methodology, it was used to build the laboratory production in the Laboratory for Machine Tools and Production Engineering. In such a production, flexibility and quality criteria need special attention because it should be possible to produce many different types of cells and they must have a high quality to carry out meaningful measurements. Due to the ease of manufacturability and the wide application, a flat pouch cell by type "High Performance" was selected. The identification of technological alternatives was carried out in working groups with representatives from industry and research. For the singular technology assessment, tests were carried out in partner companies, many experts were interviewed and the results of national research projects were used. The identification of interdependencies was based on expert interviews with employees of plant manufacturers specializing in battery production. The resulting technology chain corresponded to a large extent to previous expectations. Combinations that are not possible because of technical reasons were avoided effectively and the appropriate alternatives for the application were highlighted in almost all cases. As it turned out, the problem was to collect the needed input data, because there are only a few machinery and plant engineering companies, who address the production of lithium-ion cells directly and therefore have a sound knowledge and experience. Furthermore many companies are not pleased passing their knowledge to a research institute. The fear of losing their knowledge, and therefore their competitive advantage to a competitor, as well as the very stringent requirements of cell producers, inhibit an exchange of industry and research. The dialogue to cell producers is even worse. They almost make no information available. So there are no experiences from a running production and therefore the only input data comes from machinery and plant engineering companies. This is why the input data can be considered in a way uncertain. By a validation, together with a cell producer, this uncertainty could be significantly reduced.

## 5 Conclusion

This article presents a methodology, which assists the production planer in the conception of technology chains. The methodology is separated in four steps. The first three give information for the technology decision from different points of view and the last one generates the final technology chain. In the beginning, the requirements of process and product were defined in order to adjust the production to the aims of the customer. The value chain was designed and 128 technological alternatives were identified and evaluated by a standardized procedure. These data generated the first technology value. With regard to the specific product, the suitability of the procedures was verified and the second technology value was generated. The next step was to consider the holistic production process and to eliminate interface problems at an early stage. Therefore, interdependencies between and within the several process steps were exposed and classified. These interdependencies generated (with the help of networked thinking) the third technology value. The final step was to decide which technology value is the most important one. At least the technologies with the highest value were chosen.

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