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Assessment of Changeability in Battery Cell Production Systems

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Abstract

The production of battery cells for electric vehicles is challenged by several drivers. On the one hand, there is social awareness for climate change and shortage of fossil resources. Therefore, electric vehicles more and more become an element of automotive manufacturers portfolio. On the other hand, it is not yet decided which battery technology will prevail within the next years for automotive application. These technological issues are influenced by economic decision and result in a diversity of product variants, a development of different battery cell designs and alternatives in production technologies.
These circumstances show that battery cell production is an industry with a high pace of technological innovations and changes. In order to cope with these challenges, production systems need to be designed in a changeable manner. This research presents a methodology to assess the changeability of production systems for lithium ion and future battery technologies. Moreover, the paper provides insights into correlations and interdependencies between changeability indicators for immature product technologies.
The method is implemented and validated for a battery cell production process for Li-ion and Li-sulfur batteries. Based on the evaluation of the current Li-ion technology, it gives guidelines for the design of a changeable battery cell production system to prepare for future challenges.

Keywords: Battery Cell Production, Changeability, Lithium-Ion Battery, Production Systems

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1. Introduction

The transportation sector currently accounts for 23% of global energy-related greenhouse gas (GHG) emissions [1]. The introduction of electric vehicles (EV) is a key factor in the transition towards cleaner transportation. Battery cell production of EVs contributes up to 20% of the greenhouse gas GHG emissions of EVs over the entire vehicle life cycle [2]. Manifold new battery materials are currently under development to increase energy densities, enable fast charging and eventually lower costs for battery systems in EVs [3]. Production for these next generation batteries is still under research in comparison to production of current lithium ion batteries (LIB).

The production of battery cells is characterized by high investments required for production process technology, technical building services, dry room and automation. Investments in production goods may be battery technology-specific. A transition to new battery materials may require new production technology for some parts of the production systems. This high investment and the technology uncertainty are barriers that hinder potential cell manufacturers to build production capacities on a Gigafactory scale (annual production capacity measured in GWh), that are required to produce battery cells on a competitive cost level. A high degree of changeability of the production system may lower these barriers and help potential cell manufacturers to decide on a possible investment. Changeability assessment needs to address the technological changes and should, therefore, include the specific new battery technologies.

This paper provides an approach on assessing the changeability of battery cell production systems with the help of changeability indicators. A case is built for the production of LIB with changeability towards lithium sulfur batteries (LSB) based on literature findings. With the help of an example of the mixing process, the paper presents how guidelines may

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influence the changeability enablers identified for battery production systems.

2. Battery cell production process chain

Changeability of a production systems largely depends on the selected product, the existing production system and the production system in comparison. In this paper, the changeability of LIB cell production is assessed in comparison to LSB production. The LIB cell under study is a Li-NiCoMn prismatic cell. The selected material system and cell design have an influence on the design of the production system. Also, there is a variety of technologies available to produce battery cells. Therefore, as a first step a reference production has to be defined.

2.1. Lithium ion battery cell production process

The LIB cell production is comprised of the steps electrode manufacturing, cell assembly and cell finishing. The electrode production is predominantly a batch production process and follows the process steps: mixing, coating, drying, calendering and slitting for both anode and cathode. After electrode manufacturing, the electrodes are intensively dried and transferred to the cell assembly in the dry room. A conditioned environment with very low moisture degrees in the dry room is necessary due to the high reactivity of lithium with water. Steps within the dry room include sheet cutting, stacking, contacting, housing assembly, cell enclosing, electrolyte filling and sealing. The steps are primarily single unit production processes. The cell finishing processes of formation, aging and testing are performed outside of the dry room in temperature controlled cycling towers.

A variety of technologies are available for the same production process. The reference production technology setup used for the changeability assessment can be derived from table 1 and follows publications close to the industry [4], [5].

2.2. Lithium sulfur battery production process

In contrast to LIB mass production, LSB are produced on laboratory scale only, with individual process steps or material combinations under investigation. Hence, the reference production process is derived from the literature and patents. The process chain follows the same elements of electrode manufacturing, cell assembly and cell finishing. During electrode manufacturing there are significant differences between the production of the lithium anode and the sulfur cathode.

Different production processes have been developed for the sulfur-carbon cathode with solvent [6] and without solvent [7]. The solvent based production process represents state of the art and is therefore selected for the changeability assessment. The sulfur is mixed with carbon, binder and solvent to form a sulfur carbon composite slurry. The slurry is then coated onto the aluminum current collector with a scraper or slotted nozzle. This is followed by an airborne sheet drying process, the calendering and slitting of the cathode with a laser beam.

Production processes for thin lithium metal sheets as anodes are currently under research, as there no commercial, mechanically stable lithium metal foils available with the required thicknesses of 20µm or less.

In the anode production, Lithium is directly applied onto a collector foil, where different production processes may be used and are currently under development. For this study, a process using physical vapor deposition (PVD) of lithium onto a copper collector foil is assumed for the lithium anode coating. Due to the PVD, no mixing and no drying process is required for the anode. After coating, the anode follows through the calendering process and the laser beam slitting. All processes of the cathode manufacturing require high dry room conditions due to the reactivity of lithium and water.

The LSB cell assembly follows equivalent to the LIB cell assembly under dry room conditions. The following process steps of cell finishing may be performed according to the LIB production processes and with the same production technology.

Table 1. Reference production technology setup for LIB production.

Process step	**Reference for LIB production**	**Change in LSB**
Mixing	Discontinuous, wet	Same process for cathode, step dropped for anode
Coating	Slotted nozzle	Same process for cathode, anode[a] uses physical vapor deposition (PVD)
Drying	Airborne sheet dryer	Same process for cathode, step dropped for anode[a]
Calendering	Temperature controlled upper and lower roller	Same process technology for cathode[a] and anode[a]
Slitting	Laser beam cutting	Same process technology for cathode and anode[a]
Intensive drying	Airborne sheet dryer	Same process technology
Sheet cutting[a]	Laser beam cutting	Same process technology
Stacking[a]	Z-folding	Same process technology
Contacting[a]	Ultrasonic and laser beam welding	Same process technology
Housing assembly[a]	Hard case assembly	Same process technology
Cell enclosing[a]	Ultrasonic and laser beam welding	Same process technology
Electrolyte filling[a]	Dosing lance under protective gas	Same process technology
Sealing[a]	Laser beam welding	Same process technology
Cell finishing	Temperature controlled cycling tower	Same process technology

[a] process within dry room (for both technologies)

2.3. Process chain comparison

The differences between the two production systems mainly occur in the electrode manufacturing. During cell assembly, the lithium metal anode poses a major challenge in automated handling of sheets.

Both production processes require dry room conditions of a relative humidity below 1% at a temperature of 22°C in the cell assembly [8]. Dry rooms or microenvironments used for LIB are therefore suitable for LSB production. Additional dry room space is required for the production of lithium metal anodes used in LSB, since lithium is processed.

The comparison shows that, except of the lithium anode production, the production system design, the production processes, the required environment and the interlinking of processes of the LSB production process show significant similarity to the LIB production system. Hence, design guidelines for a LIB production systems may lead to increased changeability of this production systems towards the production of LSB cells.

3. Changeability assessment methodology

To determine the changeability of individual process steps as well as the whole process chain of a battery cell production system, a suitable evaluation methodology is required. In literature, the term changeability is defined in several ways. With the focus on production environment, changeability is considered as the potential for change [9], [10]. Changeability can be defined as “the ability of a production system to adapt quickly to changes in the environment by changing its structure" [10]. It differentiantes from flexibility and agility by the production and product level [11], [12].

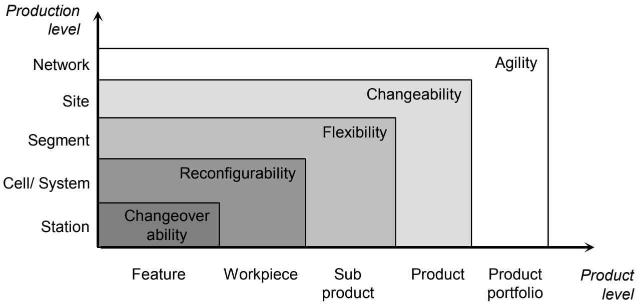


Fig. 1. Classes of factory changeability by Wiendahl [11].

3.1. Review of existing approaches

In order to be able to react to changes, a production system needs several characteristics that support the ability to change. These include in particular the five changeability enablers universality, mobility, scalability, modularity and compatibility [13]. *Universality* refers to the design of an object to meet different product or technology requirements. This primarily relates to the ability of a production facility to produce different product variants. *Mobility* refers to the local unrestricted movement of factory elements. In addition, *scalability* designates the technical, local and personnel expand- and reducibility of factory elements. The changeability enabler *modularity* describes the ability of a production system to replace standardized and independent functional units or elements [13]. *Compatibility* supports the production facilities to network with each other to exchange energy, media and information [13], [14].

In literature, there are several approaches to assess the changeability of a production system. Hernández Morales [15] has developed a methodology for a target synchronization of the changeability of a production system. In this approach, different future scenarios are definded and transferred to factory planning to achieve a target changeability. Thus, uncertainties and risks can be directly integrated into the planning process and appropriate measures can be taken already in the planning phase [15].

Based on these results, Heger [14] has developed a methodology that combines technological changeability with economic assessment. He introduces three useful tools: The changeability potential analysis evaluates the individual factory buildings.The economic analysis helps to evaluate monetary effects of different planning alternatives; the cost-utility-analysis integrates non-monetary potential benefits into changeability assessment.

A novel methodology by Sauer [16] is based on the findings of Heger. The approach includes the ability to assess the changeability of production systems of immature product technologies into a comprehensive methodology for evaluating, configuring and simulating manufacturing alternatives. The focus is exclusively on a non-monetary changeability potential analysis.

Another approach by Albrecht et al. [17] aims at evaluating the changeability of a production system by applying an integrated system dynamic and discrete event simulation approach. First, the system behaviour for a given state is analyzed with the help of a discrete event simulation. The system dynamics approach is subsequently applied to assess the changeability of a production system by analyzing the behaviour when switching between the current and a future (i.e. optimized) state.

Schuh et.al. [18] present a methodology to assess the changeability of a production system based on ERP feedback data. Due to the use of ERP data, the assessment is based on objective input and the processing and visualization occur in an online-based software tool.

The review of existing methodologogies shows that none of these are focusing on a battery cell specific assessment of changeability. Furthermore, no methodology meets the requirements for an easy application and evaluation already during product development process. By means of an early evaluation, the effects of immature battery technologies on existing production processes can be deduced andrequirements can be taken into account directly in the product development phase. In order to identify the impact of individual evaluation criteria, the methodology requires that interactions of the critera are considered during the changeability assessment.

3.2. Methodological approach

Based on the work of Heger and Sauer, this paper presents a non-monetary methodology to assess the changeability of a production system that focuses specifically on battery cell technologies. This supports the objective of accessing the changeability regarding future battery technologies that cannot be valued in monetary terms at the time of evaluation. Both the individual process steps and the entire process chain are evaluated. In addition, the method is designed to quantify

interactions between the changeability indicators and integrates them into the assessment methodology.

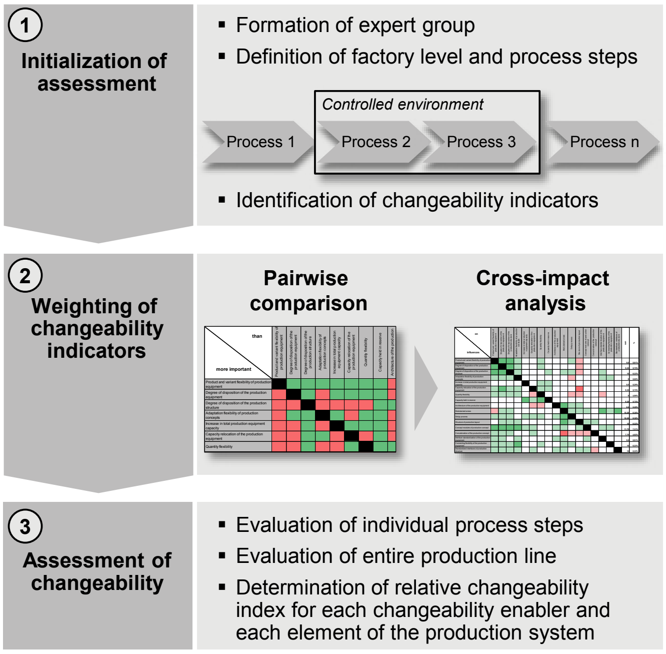


Fig. 2. Proposed methodolical approach for changeability assessment.

Figure 2 shows the procedure for evaluating the changeability of a battery cell production system, which follows a three step approach.

During the initialization of assessment, the expert group required for the assessment of changeability is formed. In this paper the expert group consists of scientific experts from different fields of the Battery LabFactory Braunschweig (BLB). Moreover, the factory levels and process steps under evaluation are defined and changeability indicators necessary for the assessment are recorded. Based on this, the previously identified changeability indicators are weighted with a pairwise comparison and a cross-impact analysis.

Finally the changeability of the entire process chain as well as individual process steps is assessed by the expert group with the aid of the changeability indicators. In this case, elements of the production system, such as process steps or technical building services can fulfill the indicators in the range of 0, 0.25, 0.5, 0.75 and 1 with 0 being the lowest and 1 the highest degree of fulfillment. By using a linear transformation function, the various results can be transferred to a value range between 0 to 100 percent. The resulting metric is defined as the relative changeability index. This metric can be used to compare different production alternatives, for example to identify process steps whose changeability is particularly low and must be increased (see chapter 4).

3.3. Changeability indicators for battery cell production

In order to carry out the changeability assessment with a focus on battery cell production, specific evaluation criteria are developed for battery technologies. The individual changeability indicators are assigned to changeability enablers as shown in table 2.

This paper uses the 17 changeability indicators proposed by Sauer [16], who derived them out of a total of 73 changeability indicators to assess changeability for immature product technologies, such as future battery cell technologies. Table 2 shows these indicators sorted by the relevance of each indicator in the changeability assessment of battery cell production systems performed by the expert group. They result from the pairwise comparison in step two of the methodological approach. As proposed by Sauer, the changeability enabler mobility is not taken into account in the assessment [16]. This is due to the interlinked production process of battery cells, which means that the mobility of the individual equipment is not necessary.

As an example one of the indicators is explained in detail. The indicator *product and variant flexibility of production equipment* refers to individual production processes and is associated with the changeability enabler universality. This indicator is used to assess whether current and future products and variants of these can be manufactured with the existing production equipment without a retrofit operation [6].

Table 2. Changeability indicators considered in this study.

ID	CE[1]	Changeability indicator	RI[2]
C1	U	Product and variant flexibility of production equipment	11.0%
C2	M	Interface standardization of the production equipment	10.3%
C3	U	Degree of disposition of the production equipment	8.8%
C4	S	Quantity flexibility	8.1%
C5	M	Architecture of the production equipment	8.1%
C6	M	Modularized areas	8.1%
C7	S	Increase in total production equipment capacity	7.4%
C8	M	Concept modules of production concept	5.9%
C9	C	Standardized interfaces of production structure	5.9%
C10	U	Degree of disposition of the production structure	5.1%
C11	U	Adaptation flexibility of production concepts	4.4%
C12	M	Setup process	4.4%
C13	S	Capacity relocation of the production equipment	3.7%
C14	M	Structure of production layout	2.9%
C15	S	Capacity held in reserve	2.2%
C16	C	Connecting flexibility of the production equipment	2.2%
C17	M	Degree of interlinking of the production system	1.5%

[1] CE: Changeability enabler, with universality (U), modularity (M), scalability (S) and compatibility (C).
[2] RI: Relevance index. Indicates the relevance of each changeability indicator as a result of the pairwise comparison performed by the expert group.

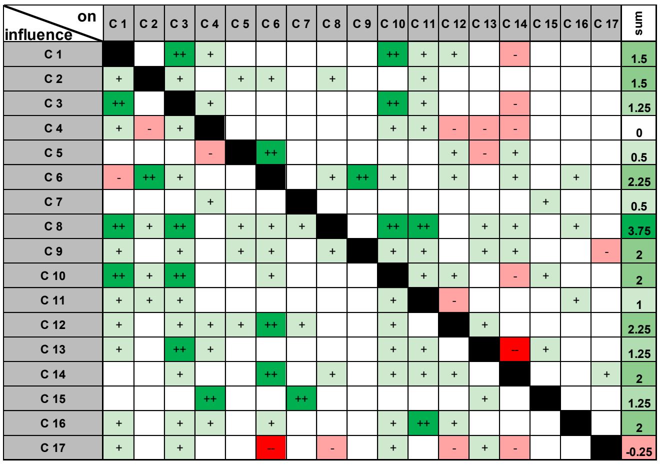
3.4. Interdependencies between changeability indicators

With the help of a cross-impact analysis correlations and interdependencies between the changeability indicators are identified and analyzed.

One indicator may have a positive, negative or neutral influence on another indicator. The evaluation was carried out by a team of experts and an ordinal scale with five options was used for the evaluation.

The results of the cross-impact interdependencies as presented in figure 3 show that most changeability indicators generally have a positive influence on other indicators. The indicator *concept modules of production concept,* which supports the integration of new products or manufacturing processes, has the highest positive interaction with other indicators. This is followed by the indicators *modularized areas* and *setup process*. This is reasonable, since a high modularity also helps other changeability indicators.

In contrast to this, the indicator *degree of interlinking of the production system* mainly has a negative influence on other indicators, due to the fact the modularity decreases with increasing interlinking of processes.



on / influence	C 1	C 2	C 3	C 4	C 5	C 6	C 7	C 8	C 9	C 10	C 11	C 12	C 13	C 14	C 15	C 16	C 17	sum
C 1	■		++	+						++	+	+		-				1.5
C 2	+	■	+		+	+		+			+							1.5
C 3	++		■	+						++	+			-				1.25
C 4	+	-	+	■						+	+	-	-	-				0
C 5				-	■	++						+	-	+				0.5
C 6	-	++	+			■		+	++	+		+		+		+		2.25
C 7				+			■								+			0.5
C 8	++	+	++		+	+	+	■		++	++		+	+		+		3.75
C 9	+		+		+	+		+	■	+	+		+	+			-	2
C 10	++	+	++			+				■	+	+		-	+			2
C 11	+	+	+							+	■	-				+		1
C 12	+		+	+	+	++	+			+		■	+					2.25
C 13	+		++	+						+	+		■	--	+			1.25
C 14			+			++		+		+	+	+		■			+	2
C 15				++			++						+		■			1.25
C 16	+		+	+		+				+	++	+				■		2
C 17	+		+			--		-		+		-	+	-			■	-0.25

Fig. 3. Interdependencies between the changeability indicators.

3.5. Results of the changeability assessment

The changeability assessment is performed as a comparative assessment of the LIB and LSB production process detailed in section 2 on a single process and on a process chain level with the help of the expert group.

The results of the changeability assessment for the process chain show that the cell finishing achieves the highest relative changeability index of 100 percent. Relative to this production area, the cell assembly of the reference production systems achieves a value of 76 percent, while the electrode production reaches the lowest value of 66 percent.

The results of the changeability assessment of the individual enablers are displayed for each process step as a heat map in figure 4. Overall, there is a clear variance of changeability between the individual process steps. The highest value is achieved by the cell testing process step during the cell finishing and obtains a relative changeability index of 100 percent. In total, the process step drying of the electrode achieves the lowest relative value with 58 percent compared to the best process step. This can be explained by the high degree of interlinking of the drying process determined by the expert group.

Using the example of the mixing process, the results of the changeability assessment are interpreted in more detail. Within the electrode production, the process of mixing the slurry has a relative changeability of 61 percent. With respect to the individual changeability enablers, scalability has a low relative changeability of only 20 percent. The reference process is a discontinuous batch mixing process, in which the quantity of a batch cannot be easily adapted. Furthermore, the process step has a low average changeability in terms of compatibility. For example, the slurry is produced in large batches and must be supplied to the subsequent coating process step in smaller quantities, which results in additional handling effort between the process steps.

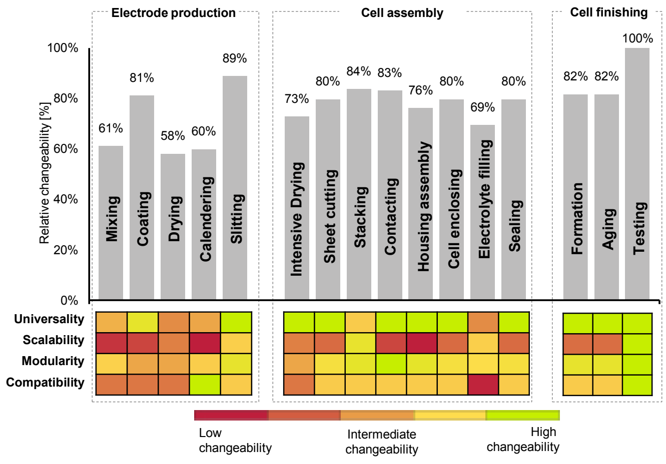


Fig. 4. Results of the changeability assessment for LIB and LIS.

Concluding, the integration of a LSB into an existing lithium-ion battery cell production can be supported from a manufacturing point of view, because there are only few adjustments necessary. However, the electrode production and specifically the lithium metal anode production requires new production technology that is not found within LIB production systems. Concerning future battery cell production facilities, the combined production of the two battery technologies poses some challenges for which necessary adaptations can be considered during the planning process.

4. Guidelines for a changeable battery production

Regarding the configuration of a future changeable battery cell production system, the cross-battery technology use of the production equipment may be particularly important from an economic and technical point of view. This study shows that some but not all process steps may be used to produce both battery technologies LIB and LSB. The changeability assessments shows that the process steps mixing, drying and calendering have a low relative changeability index and must be redesigned to be used in a changeable factory.

To assist the design of the process step mixing regarding its use in a changeable battery cell production, various design guidelines can be derived. These guidelines were identified and discussed in the expert groups, as a fully systematic approach was not feasible. In general, a development from a discontinuous to a continuous process is recommended for the mixing process step. In order to increase the changeability enabler universality, product-specific tools for the continuous mixing process must be avoided. This ensures that different material compositions can be produced with the same production equipment and simple adaptions of it. By using a continuous mixing process with the functional principle of an extruder, the lead time and mixing time can be reduced and the scalability can be increased. In addition, the compatibility of a production equipment can be improved by providing intermediate products to subsequent process steps as required by this process. With a continuous mixing process, the exact amount of slurry required for the subsequent coating process is produced continuously.

In order to validate the guidelines, the optimized process step mixing is assessed once again with a group of experts, following the same methodological approach as before and with the results shown in figure 5. By applying the design guidelines it has been possible to significantly increase the changeability of the process step to 81 percent, which means a changeability increase of could be increased by 33 percent. Regarding the enabler universality, it was possible to achieve an improvement from 67 percent to 89 percent. Moreover, the scalability could be improved from 30 to 59 percent. Even there was no guideline derived for modularity, the changeability could improve from 77 to 87 percent due to interdependencies between the changeability enablers. A particularly large effect was achieved with regard to compatibility. In this context, an increase in the relative changeability from 50 to 100 percent has been achieved through the design guidelines.

5. Summary and Outlook

This paper suggests a methodology to assess the changeability of battery production systems based on a comparison of a reference lithium ion battery cell production and a possible production system for lithium sulfur battery cells. The methodology provides insights into relevant changeability indicators and their interactions for battery cell production. From the resulting relative changeability indicator for each changeability enabler and each process step, improvement guidelines can be derived.

In the considered case of lithium sulfur batteries, the reference lithium ion production system contains all necessary processes, ambient conditions and production equipment for cathode production, cell assembly and cell finishing. The provided exemplarily guidelines for the mixing process show that they positively influence the changeability, specifically with the change from batch to continuous production. Recent research efforts on continuous mixing processes for electrode production support this.

Research on coming battery generations, such as all-solid-state batteries, indicate that the change in production equipment is fundamental. The results and the methodology of this paper may be used to support changeability in the structural change of battery cell production systems. However, the presented changeability assessment addresses a specific reference case and uses a similar expert group throughout the process. In order to reach a higher degree of objectivity, the expert group should be enlarged. Due to the choice of changeability indicators, the assessment is specific for battery cell manufacturing. Different applications may require other changeability indicators.

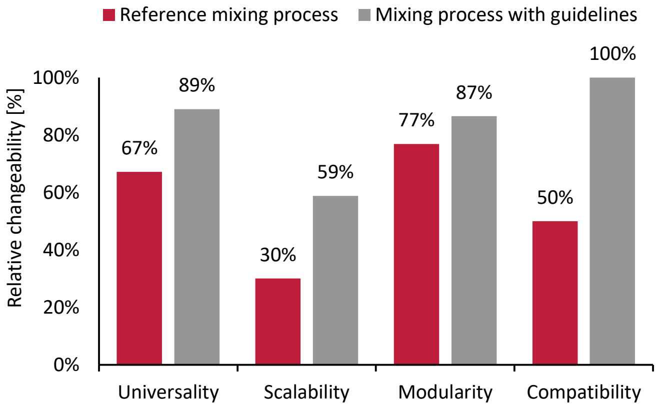


Fig.5. Results of validation of the design guidelines for mixing process.

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