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Conception Of Future-proof Factory Buildings Via Software-based Scenario Creation And Evaluation

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Abstract

Due to internal and external change drivers, manufacturing companies must adapt their production systems regularly. Factory buildings typically have a service life of several decades and, therefore, must accommodate multiple generations of production systems. To achieve this, buildings require a design that is universal to a certain degree yet adaptable when universality is not sufficient – buildings must be future-proof. Such a design requires anticipating potential future requirements and deciding which requirements to fulfil. Methods from the research field of foresight, especially the scenario technique, can support this process. However, these methods often require extensive calculations, making software support mandatory.

This paper first provides an overview of the state of research on scenario-based planning of future-proof buildings and introduces a previously developed planning method. It then identifies requirements regarding a respective software tool. Afterwards, the paper presents the development of such a tool's prototype. Finally, the tool is deployed in a case study that covers planning a battery cell production facility to validate its function. The case study demonstrates that the method, in combination with the tool, effectively supports the planning of future-proof factory buildings. It thereby prolongs the service life of factory buildings by facilitating easy adaptions of the production systems within.

Keywords

Factory Planning; Changeability; Flexibility; Transformability; Industrial Construction; Scenario Technique

1. Rigid structures in a turbulent environment

Internal and external change drivers force manufacturing companies to adapt their production regularly to changed requirements to keep their competitiveness [2,1]. Compared to the elements of the production system, the factory building typically has a much longer service life [3]. Depending on the industry, the service life may range up to one century [4]. Especially the load-bearing structure can hardly change and stays in use for the whole service life of the building [3]. Shortening the service life of factory buildings to adapt regularly to current requirements is no suitable option from an economic and ecological perspective [6,5]. Consequently, the factory building must be able to accommodate multiple generations of production systems. To achieve this, the building must have a design that is universal to a certain degree yet adaptable when universality is not sufficient – it must be future-proof.

Some strategies to improve future-proofness, like decoupling building components to allow easy maintenance and replacement [7], can be followed to a certain extent independently of the project. However, most measures to raise future-proofness, like reserve capacity [7], are directly linked to costs and need thoughtful planning. While the marginal benefit of a higher ability to accommodate change decreases, the

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additional costs are rising disproportionately [8]. Consequently, it is not reasonable to strive for a factory that is prepared for arbitrary future contingencies. Instead, planners must anticipate potential future requirements in consultation with the user and decide whether to fulfil these or deliberately exclude them. [6,10,9] Factory planning involves planning for long time horizons. An exact prediction of potential future requirements is, therefore, not possible. The research field of 'foresight' is based on the fundamental assumption that there are various possible futures, and it is not yet certain which of these futures will occur [11]. Its methods deal with the exploration of these possible futures [12]. The methods, especially the scenario technique, are well suited to support the requirement identification in factory planning [13]. As these methods require extensive calculations, software support is mandatory to handle the effort [6].

The ability of a factory to suit different requirements either by its existing properties or by changing itself to suit the requirements is a much-discussed topic in production engineering. The same applies in architecture regarding the suitability of buildings for changing requirements. [6] In both disciplines, many terms denote different dimensions of this ability (see [16,15,14]). This paper uses the term ‘transformability’ as a general term for the ability to suit changing requirements. ‘Flexibility’ and ‘changeability’ are specific manifestations of this general term. Flexibility takes place within installed technical capabilities in a defined flexibility corridor. In contrast, changeability goes beyond the installed technical capabilities and shifts or resizes the flexibility corridor. However, an explicitly or generically preconceived changeability corridor limits the potential for change due to economic reasons. [17,18]

The following Section 2 provides an overview of existing methods for planning future-proof facilities using scenario techniques in production engineering and architecture. It also presents one previously developed method focusing on factory buildings in more detail. Based on this method, section 3 identifies the requirements for a software tool to support the scenario-based planning of future-proof factory buildings before section 4 presents the development of such a tool’s prototype. Afterwards, section 5 deploys the tool in a case study that covers planning a battery cell production facility. Finally, section 6 summarizes the paper and provides an outlook.

2. Scenario-based planning of future-proof facilities

As *Brand* noted: “All buildings are predictions. All predictions are wrong.” [19] However, considering potential futures can improve the future-proofness of buildings. Scenario techniques are suitable for envisioning potential futures and identifying resulting requirements [19,20]. Some planning approaches in production engineering and architecture already use scenarios. The following section discusses these approaches.

2.1 Methods in production engineering and architecture

The use of scenario techniques in production engineering is particularly popular in Germany. *Hernandez Morales* published the first comprehensive planning approach based on scenario management by *Gausemeier et al*. (see [21,22]). The approach divides the factory into so-called factory objects distributed across all production levels and various design fields. The ‘building’ is one of these factory objects and is, in turn, divided into the sub-objects 'structure', 'cladding', 'services' and 'interior fit out'. The method first develops different scenarios and then estimates their effect on the factory objects. [23]

Subsequently, several authors have developed procedures for scenario-based planning, some of which are based on *Hernandez Morales'* work. *Heger* developed a procedure for assessing the changeability of factory objects. He bases the identification of requirements on the scenario technique, although he focuses on a single scenario instead of planning future-proof. [24] *Koch* combines the two procedures with a third approach for planning socio-technical adaptability. As noted by the author, the procedure becomes very effortful and time-consuming. Therefore, he suggests replacing several methods with expert interviews. [25] *Albrecht* develops a method to evaluate the transformability of production systems using simulation. He uses the scenario technique to determine the simulation's worthiness and to identify scenario-specific input variables for the simulation model. [26]

All authors, except for *Albrecht*, include the building in their method. However, it accounts only for a small share of the vast and heterogeneous area under consideration. The approaches do not detail the properties of factory objects like the building structure. This makes it challenging to derive effects from the scenarios on the objects. In addition, all approaches require significant effort due to their methodological structure. [6]

Considerations of using scenarios in architecture date back to the early 1990s (see e.g. [27]). However, it is only sparsely applied [28]. *Brand* published the first procedure to apply scenarios in architecture in 1995. He suggests using scenarios in the initial phase of a building design project or after preliminary programming. Therefore, applying the procedure can either change the vision of the building or analyse the effects of different futures on the preliminary program to improve the 'robustness' of the building concept. [19] The presented procedure provides only loose guidance and lacks a systematic process for deriving requirements from scenarios.

Galle et al. present a procedure to integrate scenarios in the planning of residential buildings. It is more detailed than *Brand's* procedure and provides more guidance. It analyses different design alternatives in different futures and focuses on the respective cost effects. The authors suggest using digital modelling techniques like building information modelling (BIM) to translate the scenarios into detailed effects on the building and, subsequently, costs but do not detail this step of the procedure. [28] The procedure of *Galle et al.* requires existing design alternatives and challenges them against different futures. In contrast, *Kaucher et al.* present a method that creates the design according to scenarios. It has a production engineering background but focuses specifically on the factory building. [6] The following section outlines this method as the background of the developed tool.

2.2 Planning method for future-proof factory buildings

The planning method for future-proof factory buildings (see [6]) is executed in three steps during phase three, 'concept planning', of the factory planning procedure of VDI 5200 (see [29]). Figure 1 presents an overview of the method's three steps. The method is suitable for use in both greenfield and brownfield projects. However, its application in greenfield projects offers greater potential due to the higher degree of freedom. This section provides a theoretical description of the method while section 5 presents a detailed application example as a case study.

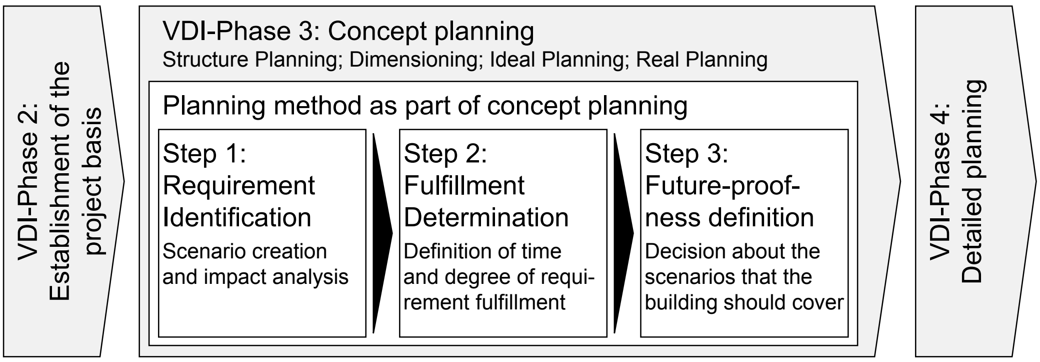


Figure 1: Structure of the presented method [6]

The initial step of the method involves identifying potential future requirements. To achieve this, the method generates scenarios using a procedure based on the scenario management of *Gausemeier et al.* [21]. The method starts by recording significant potential changes in the company and its environment as 'key factors'. A set of standard influential areas that describe the company and its environment has been developed to support the identification of key factors. A separate article will present this model. One of the influential areas is 'production and infrastructure'. A factor of this area could be a change in a key production technology. A key factor can take on the characteristics of 'does not occur' and 'occurs'. A consistency analysis evaluates the joint occurrence of two key factors, ranging from absolute inconsistency to absolute consistency. A so-called consistency matrix that displays the possible combinations supports this analysis. There are four combinations for each key factor pairing, starting with the non-occurrence of both factors: $\neg A \wedge \neg B$; $A \wedge \neg B$; $\neg A \wedge B$; $A \wedge B$. The consistency analysis is conducted during a workshop with the project team. In order to ensure a uniform understanding of the different consistency assessments, it is advisable to provide a brief description of them at the outset of the workshop. The combination of all key factors (n) in their two values results in 2^n different 'projection bundles'. The method excludes consistency bundles with total inconsistencies or a low sum of consistency. Afterwards, a cluster algorithm forms 'raw scenarios' from the remaining bundles, briefly formulated in text form.

At the same time, an impact analysis examines which requirements each key factor places on the building in case of its occurrence. The influence analysis employs a 'domain mapping matrix' (see [30–32]) to relate the key factors on the vertical axis with the building's functional units and their essential properties, such as floor load-bearing capacity, on the horizontal axis. An evaluation then determines if a key factor has an impact, and if so, the effect is described and assessed.

The second step involves developing measures to address these effects and assigning the corresponding costs. Depending on the characteristics of the building parameters affected by the requirements, various measures are possible. The parameter can be oversized from the beginning, retrofitted if necessary, or technical or organizational alternatives can be explored. The corresponding costs for each measure need to be assessed by the respective experts from architecture. If multiple measures are possible to cope with one effect, one measure is selected based on a target system.

The costs incurred to prepare for each key factor can be determined based on the measures and resulting costs defined in the previous step. Additionally, each scenario specifies which key factor is included in the form of 'occurs'. This allows the determination of the costs incurred to prepare the building for each scenario. In the final step of the method, users select a starting scenario that must be fulfilled in every case and arrange the remaining scenarios based on the minimum additional costs compared to the already arranged scenarios. Strategic decisions on the preparation scenarios are required at points where there are significant cost jumps in the arrangement. It is important to evaluate the respective differences in the scenarios at these points in detail.

Considering consistent scenarios ensures the design of an attuned overall concept. This structured approach makes requirements and additional costs transparent, allowing for a well-founded decision on future-proofness. Additionally, it reduces the number of decision points in the planning process, as it considers scenarios rather than individual requirements. The procedure is computationally intensive and, therefore, requires software support. The following two sections discuss the development of an appropriate tool.

3. Requirements set to an appropriate software tool for panning future-proof factory buildings

The requirements definition is based on the use case of supporting the presented method for planning future-proof factory buildings. It classifies the identified requirements into two types: functional requirements and non-functional requirements. Functional requirements describe the capabilities a software must have, while non-functional requirements describe the properties of software, also known as quality attributes. [33]

The application must be capable of supporting the method sequence throughout (requirement (req.) 1). To achieve this, it must automatically generate a desired number of scenarios based on key factors and consistency analysis. Therefore, it must create the projection bundles, reduce them and apply a clustering algorithm to create the scenarios. To ensure a broad and uniform representation of the future space, it must use an algorithm which forms uniform scenarios instead of a few very large ones and some outliers. The complete linkage algorithm is such an algorithm [34]. Additionally, the tool must support the impact analysis using a domain mapping matrix and the documentation of the subsequently developed measures to fulfil the resulting requirements. Finally, the application should determine the costs per scenario based on the measures' costs. The user selects a starting scenario, and the application sorts the remaining scenarios according to the minimum additional costs.

Primary users of the tool are factory planners. They use it in workshops and for their preparation and follow-up. However, input is required from different players due to the interdisciplinary nature of factory planning. To avoid a wide distribution and training of the application, it must be capable of importing corresponding Excel templates for input parameters like key factors and consistency analysis in addition to creating them in the software. Only the factory planner needs to be familiar with the software, while other stakeholders can work with the templates (req. 2). To ensure easy distribution of results, they must be exportable in standard formats such as Excel (req. 3).

No.	Requirement	Type
1	Comprehensive support for all three steps of the method	Functional
2	Import function for Excel templates with main input parameters	Functional
3	Export function for results in standard formats such as Excel	Functional
4	Operation via a graphical user interface (GUI)	Non-functional
5	No special requirements for the performance of the computer	Non-functional
6	Calculation of scenarios (20 key factors) in 15 minutes or less	Non-functional
7	Use of a high-level programming language	Non-functional
8	Modular structure of the application	Non-functional

Figure 2: Identified requirements for the application

Factory planners using the tool may not possess any special expertise in programming. To ensure ease of use, the tool must have a graphical user interface (GUI) (req. 4). It must not place any particular demands on the computer's performance to enable seamless use of the application in workshops (req. 5). Additionally, the computing time must be low enough to avoid any restrictions on its use in workshops. Therefore, the total calculation time for the steps leading up to the presentation of the scenarios for 20 key factors must not exceed 15 minutes (req. 6).

To ensure ease of maintenance as well as modifiability and expandability, the application must be written in a widely used high-level programming language (req. 7) and have a modular structure (req. 8). Figure 2 provides an overview of the requirements, classified into functional and non-functional categories.

4. Development of a software prototype

The application is based on Python, a widely used high-level programming language (req. 7) [35]. It comprises a main module and two further modules containing the functions required for scenario creation and impact analysis (req. 8).

The application has five main functionalities, each with several sub-functionalities. These encompass defining key factors, including the consistency assessment, the creation of scenarios, the instantiation of a building model, the impact analysis, and the definition of future-proofness. The application therefore has functions to support all three steps of the method (req. 1). It has import functions for the key factors and consistency assessment, the functional units and relevant building parameters, and the impact list (req. 2). The application can import the data from an Excel template or create it directly in the application. There are also export functions for a scenario overview and a detailed report, the impact list and the overview for defining the future-proofness (req. 3). The implementation of the functionalities involves the use of several Python libraries, such as pandas, SciPy, NumPy, and Matplotlib. The application provides a GUI based on the Tkinter GUI toolkit, making it accessible to users without programming expertise (req. 4). Figure 3 displays the tool's GUI and a results table for the third step. The dark green buttons represent the five main functionalities, while the light green buttons appear as submenus for each main functionality.

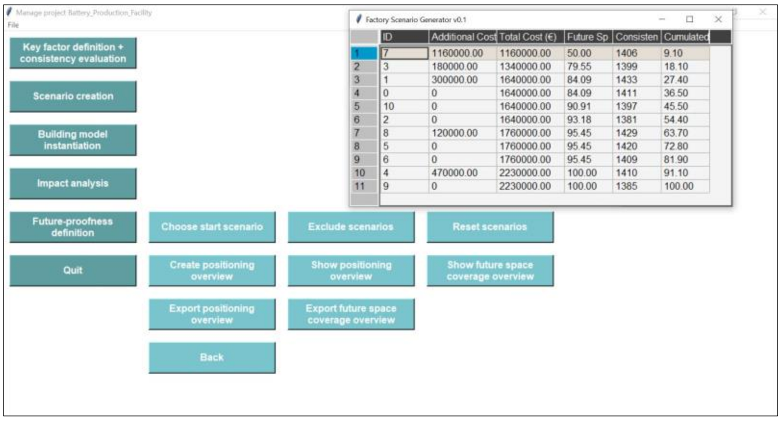


Figure 3: Screenshot of the application with the menu and the results table from step 3

The application was tested on a conventional computer with an Intel® Core(TM) i7-8565U processor and 16 GB of RAM (req. 5). The calculations to create the scenarios took approximately 1.75 minutes with 20 key factors (req. 6). Although the calculation time increases non-linearly, the computer even managed to complete the calculation for the case study with 22 key factors (section 5) in 11.5 minutes. In summary, the application meets all the requirements outlined in section 3. The following section presents the application of the method presented in section 2 in combination with the software-prototype in a fictitious case study.

5. Case study: Scenario-based planning of a future-proof production facility for battery cells

The case study refers to planning a production facility for lithium-ion battery cells. It is loosely based on experiences from the planning of the »FFB-Fab« and the »FFB-PreFab«, two research production facilities in Münster, Germany. However, as a simplification, it assumes a regular industrial manufacturing company.

5.1 Presentation of the company

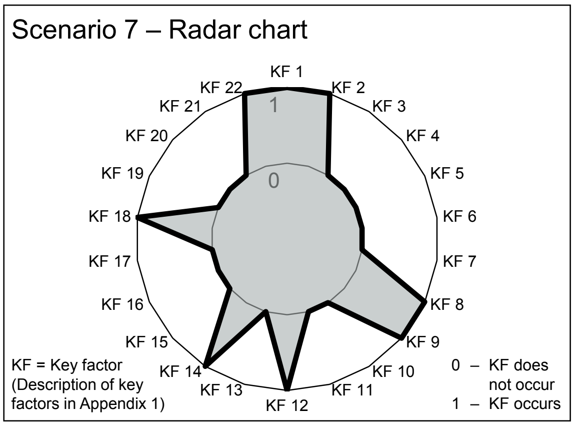
The company discussed is the ‘Power Tool Cell Corporation’ (PTCC), a subsidiary of a manufacturer that produces power tools for the premium segment and professional applications. Previously, the parent company sourced its cells from suppliers. However, in recent years, it has developed expertise in producing lithium-ion cells and now aims to produce them in the subsidiary. The sales forecast predicts a yearly demand for approximately 1.5 million battery packs in the future. A battery pack has an average capacity of 150 Wh. Therefore, the company requires a production capacity of at least 225 MWh. The lithium-ion cells used in the packs have the format 21700 and are based on carbon as the anode and NMC622 (lithium nickel manganese cobalt oxide) as the cathode material.

The company now plans to build a respective factory in Germany with the support of an external factory-planning consultancy. As it operates in a highly volatile market, it wants to plan the factory future-proof. Therefore, it applies the presented method in combination with the tool in the planning process.

5.2 Application of method and tool

First, a workshop examined the areas of influence around the company and identified the most important influencing factors as key factors. 22 key factors were identified, including, for example, the switch to nickel-rich NMC mixtures as the cathode material as well as the acquisition of an external customer in addition to the parent company. Appendix 1 shows a complete list of the identified key factors. The team evaluated the consistency of each of the key factor combinations. For example, it assessed the consistency of the joint appearance of nickel-rich cathode materials and an external customer positively, as external interest in the company's cells is considered higher with modern cell chemistry.

In the following step, the consultants utilised the tool to create future scenarios based on the assessments and agreed upon them with the company. Figure 4 presents an example of such a scenario. The team set a target value of at least seven scenarios, with the clustering algorithm ultimately resulting in eleven scenarios. Appendix 2 displays the eleven scenarios in coded form. The project team conducted a workshop to analyse the requirements that the key factors impose on the factory building. Among other things, it was determined that processing nickel-rich NMC compounds requires a lower dew point than initially planned. The team assessed the resulting requirements in terms of their severity of impact, including the cost and effort required to implement measures to fulfil the requirements after the construction of the building.



Scenario 7 – 'Modernised cell design'

There is positive economic development, which is also reflected in increased demand for cells on the global market. However, this high demand results in a worldwide shortage of the raw material cobalt. To address this issue, there is a growing trend towards nickel-rich cathode materials with lower cobalt content, such as NMC811.

PTCC is also switching its production to nickel-rich cathode materials. In the future, PTCC manufactures its cells in the 4680 format instead of the current 21700 format. As a side effect, these changes lead to a higher number of variants.

The positive developments in the global market and the introduction of the new, modern cell design generate increased external interest in PTCC's cells. Consequently, PTCC secures a contract with an external customer for the supply of high-end cells.

Figure 4: Characterization and description of scenario 7 'Modernised cell design'

In another workshop, the project team devised measures to address the requirements, evaluated them, and made a selection. For instance, when it came to the need for a lower dew point, the team decided against installing the necessary additional drying units in the assembly area from the beginning. Instead, they opted to prepare only the ventilation technology and available technical space. The estimated cost for this was €300,000. It is important to note that the definition of the measure does not guarantee its implementation. The decision to implement the measure is made only in step 3 of the method. Appendix 3 shows an excerpt of the impact list, including measures and associated costs.

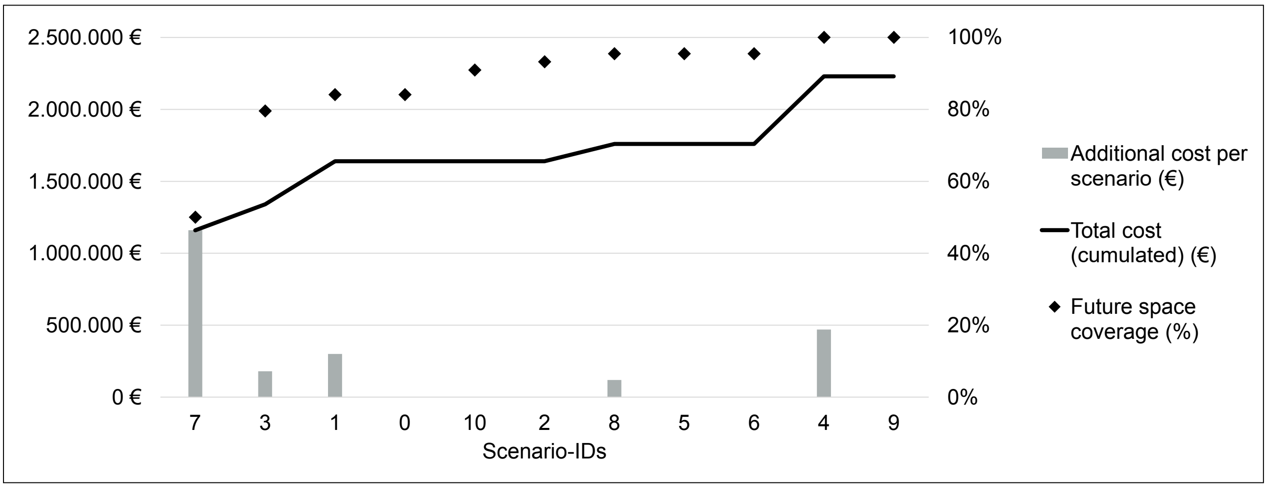


Figure 5: Future-proofness positioning diagram from the case study

Finally, the project team had to determine the scenarios that the building should fulfil and the resulting measures for construction. They started by selecting a baseline scenario that the building must meet. The team opted for scenario 7 (see Figure 4). The tool then calculated the costs of fulfilling the scenario and arranged the remaining scenarios based on the minimum additional costs. If scenarios have the same additional costs, the tool sorts them by consistency. It also determined the future space coverage in each case, i.e., what percentage of the 44 possible binary key factor characteristics are contained in the arranged scenarios. Appendix 4 shows the output data from the tool for the subsequent generation of the positioning diagram in Figure 5. The diagram illustrates the extent to which fulfilling specific scenarios incurs additional costs. The selected start-scenario 7 initially causes high additional costs of more than €1.000.000. However, it is normal for the first scenario to cause high additional costs to a certain extent. Additionally, the project team deemed scenario 7 highly realistic and, therefore, decided that the building must fulfil it regardless.

The project team then analysed the differences between each scenario at a jump point and the previous ones and decided whether to accept the additional costs. In scenario 1, the cost difference is mainly due to the preparation for the future introduction of mini-environments in assembly. If scenarios are not to be fulfilled in the course of the diagram, they can be excluded and the diagram updated accordingly. The team decided to fulfil all scenarios except for scenarios 4 and 9. The additional costs in these scenarios are mainly due to preparation for dry coating. The team rejected this, as it considered its relevance too uncertain. The measures required to meet the selected scenarios were then incorporated into the building planning process. The additional costs for future-proofness amount to about €1.750.000.

5.3 Discussion

The case study shows that the method, in combination with the tool, effectively supports planning future-proof factory buildings. The workshop-based approach ensures the close involvement of the company's relevant experts, which is necessary for factory planning [1] and foresight studies [36].

Comprehensive consideration of the building's future-proofness increases the planning effort compared with conventional planning. However, planning costs represent a very small proportion of the total cost of a building over its lifecycle. At the same time, future-proof design has the potential to avoid expensive conversions and extend the building’s service life. The additional effort in the planning process, therefore, seems justified. Moreover, the effort is reduced significantly compared to other approaches in this area. On the one hand, this is due to the design of the method, which, among other things, limits the number of key factors and only expresses them in binary form. On the other hand, the developed tool considerably simplifies the application and guides the user through the process.

Determining the appropriate number of scenarios posed a challenge in the case study. In addition to analyzing the content of the generated scenarios, mathematical approaches for determining the optimal number of clusters, such as scree plots, can provide support here [22]. Initial tests are already showing promising results.

6. Conclusion and outlook

This paper presents a tool for supporting future-proof planning of factory buildings. It first introduces the subject area and then provides an overview of existing methods for future-proof planning in production engineering and architecture. Afterwards, it discusses one method focusing on the factory building in particular. The paper derives requirements for the supporting tool based on the presented method and the use case of the tool. Afterwards, it describes the development of the tool. Finally, the tool is applied in a fictitious case study to validate its suitability for the use case.

The case study confirmed the suitability of the tool. However, it revealed some small potential for improvement, such as integrating mathematical support for selecting the appropriate number of scenarios. Overall, the method, in conjunction with the application, effectively supports planning future-proof factory buildings. The additional effort seems justified due to the increased future-proofness. The next step is to apply the method and the tool in an actual factory planning project.

Acknowledgements

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Appendix

Appendix 1: Table of all key factors

The following table presents the 22 key factors identified in the case study. Each factor can have two possible values: 'occurs' and 'does not occur'.

No.	Key factor	Description
1	Ni-rich cathode materials	Switch of the cathode material of the cells to more nickel-rich materials such as NMC811 in order to reduce the cobalt requirement and exploit advantages in terms of capacity.
2	4680 format	Change of cell format from 21700 to 4680 due to cost, energy and power density advantages.
3	LFP cathode material	Due to its lower price, easier processability and robustness, LFP will be introduced as a further cathode material in addition to the NMC used to date.
4	Mini environments	Conversion of the assembly to mini-environments. The systems are encapsulated so that the dryness requirements in the surrounding area are reduced.
5	Continuous mixing	Conversion of the mixing process from a batch process to a continuous mixing process. This allows continuous process monitoring and direct intervention in the process and thus offers advantages in terms of quality.
6	Dry coating	Conversion of electrode production to dry coating so that the drying line and parts of the infrastructure can be omitted.
7	Laser drying	The coating oven drying section is combined with upstream laser drying. This allows the length of the oven to be reduced, thereby reducing gas consumption and the overall drying footprint.
8	Continuous vacuum drying	For the vacuum drying process step, the technology is converted from a batch process in vacuum ovens to a continuous roll-to-roll vacuum drying process. This reduces process time, energy consumption and footprint and improves quality.
9	External customer	Additional supply of cells amounting to 50 MWh to an independent customer with a different focus in the power tools sector.
10	Low-cost product line	Introduction of a low-cost product line by the parent company. Volume production of the required cells takes place in a separate plant or the cells will be purchased. However, as the lead plant, the currently planned plant must have the expertise for low-cost cells and serve to balance capacity.
11	Differentiation	The parent company is pursuing a differentiation strategy. In this context, battery packs with specific characteristics are being introduced (long-life, high-power, etc.)
12	Increase in internal demand	Demand from the parent company increases by 25%. As a result, the need for cells increases accordingly.
13	Decrease in internal demand	Demand from the parent company decreases by 25%. This also reduces the need for cells to a corresponding extent.
14	Increase in number of variants	The number of cell variants produced increases by 50%. The production batches become correspondingly smaller.
15	Asian competitor	An Asian company is increasingly developing from a supplier in the low-cost sector into a supplier in the high-end and professional sector, putting pressure on the parent company.
16	Cell oversupply	Internationally, there is a significant oversupply of cells, which leads to falling prices.
17	Subsidization	The state launches a support program for the introduction of climate-friendly technologies in companies.
18	Shortage in Cobalt	There is a shortage of cobalt for cathode materials on the global market, which is accompanied by rising prices.
19	Hedge fund takeover	An investment fund takes over the parent company and focuses increasingly on maximizing profits quickly.
20	Declining research intensity	National and international research funding, and therefore research intensity, declines significantly (e.g. due to other priorities such as hydrogen or a generally weak economic situation).
21	Weak economy	Economic growth in Europe, the parent company's most important market, has stagnated over a longer period of time.
22	Upswing	Economic growth in Europe, the parent company's most important market, increases and remains at a high level for an extended period of time.

Appendix 2: List of scenarios in codified form

The following table presents a coded list of the case studies scenarios in its columns. Each scenario contains all key factors (KF; rows of the table), either in the characteristic ‘does not occur’ (‘0’) or ‘occurs’ (‘1’).

The consistency value in the penultimate row of the table shows the sum of all individual consistency ratings between two key factors in their respective characteristic. The possible ratings are ‘1’ (absolute inconsistency), ‘2’ (partial inconsistency), ‘6’ (neutral), ‘8’ (high consistency) or ‘9’ (absolute consistency). As indicated in section 2.2, the consistency matrix contains the consistency rating for all possible key factor combinations. To calculate the consistency value of for example scenario ‘0’, the consistency values of the following combinations need to be summed up from the consistency matrix: KF 1 ‘1’ with KF 2 ‘1’, KF 3 ‘0’, … KF 22 ‘1’; KF 2 ‘1’ with KF 3 ‘0’, … KF 22 ‘1’; … ; KF 21 ‘0’ with KF 22 ‘1’.

The method rejects projection bundles with total inconsistencies. Therefore, the scenarios can only contain partial inconsistencies. The last row of the table gives the number of partial inconsistencies.

Scenario-IDs	0	1	2	3	4	5	6	7	8	9	10
KF 1: Ni-rich cathode materials	1	1	1	0	0	1	1	1	1	0	1
KF 2: 4680 format	1	1	1	0	1	1	1	1	1	0	1
KF 3: LFP cathode material	0	1	1	1	0	0	1	0	1	1	0
KF 4: Mini environments	1	1	1	0	1	1	1	0	1	1	1
KF 5: Continuous mixing	0	0	0	0	1	1	1	0	1	1	0
KF 6: Dry coating	0	0	0	0	1	0	0	0	0	1	0
KF 7: Laser drying	1	1	0	1	0	1	1	0	1	0	0
KF 8: Continuous vacuum drying	1	1	0	1	0	1	1	1	1	0	0
KF 9: External customer	1	1	1	0	0	1	1	1	0	0	1
KF 10: Low-cost product line	1	1	1	1	0	0	1	0	1	1	0
KF 11: Differentiation	1	1	1	1	0	0	1	0	1	1	1
KF 12: Increase in internal demand	1	1	0	1	1	0	0	1	1	0	0
KF 13: Decrease in internal demand	0	0	1	0	0	1	1	0	0	1	1
KF 14: Increase in number of variants	1	1	1	1	0	1	1	1	1	1	1
KF 15: Asian competitor	1	1	1	0	0	1	1	0	1	1	1
KF 16: Cell oversupply	0	0	1	1	0	0	0	0	0	1	0
KF 17: Subsidization	1	1	1	1	0	1	1	0	1	1	1
KF 18: Shortage in Cobalt	0	1	1	0	0	1	1	1	1	0	1
KF 19: Hedge fund takeover	0	0	1	0	0	0	1	0	0	0	0
KF 20: Declining research intensity	0	0	0	1	0	0	0	0	0	1	0
KF 21: Weak economy	0	0	1	1	0	0	0	0	0	1	0
KF 22: Upswing	1	1	0	0	1	1	1	1	1	0	0
Consistency	1411	1433	1381	1399	1410	1420	1409	1406	1429	1385	1397
Partial inconsistencies	14	15	31	14	4	10	21	8	14	22	13

Appendix 3: Excerpt from the impact list

The following table shows an excerpt from the impact list with triggering key factor, affected functional unit and building parameter, impact intensity, a short description and a description of the impact and the identified measure as well as the resulting costs.

Key Factor	Functional unit	Building parameter	Impact	Short description	Description and Measures	Financial impact (€)
KF 1: Ni-rich cathode materials	Electrode Production (Cathode)	Floor Space	2	Add. technical facilities for dew point reduction	In the event of a switch to nickel-rich cathode materials, the dew point must be lowered. For this purpose, additional technical space is provided for the installation of drying units in the future. In addition, various preliminary work is required with regard to technical installations.	€150,000
KF 1: Ni-rich cathode materials	Assembly	Floor Space	3	Add. technical facilities for dew point reduction	In the event of a switch to nickel-rich cathode materials, the dew point must be lowered. For this purpose, additional technical space is provided for the installation of drying units in the future. In addition, various preliminary work is required with regard to technical installations.	€300,000
KF 5: Continuous mixing	Mixing	Floor Loading (Point)	2	Increased point loads for mixer	A higher permissible point load in the mixing area is required for the subsequent installation of a continuous mixer.	€120,000

Appendix 4: Data basis of the positioning diagram generated with the scenario tool

The following table shows the basic data of the positioning diagram generated by the application. Starting from the selected starting scenario 7, the other scenarios are arranged according to the minimum additional costs. The additional costs for each scenario are shown in the second column. In addition, other key values are given: cumulative additional costs of all scenarios arranged up to this point, coverage of the future space (i.e. all 44 possible key factor characteristics) by the scenarios arranged up to this point as a percentage, consistency value of the respective scenario, as well as the share of the cumulative consistency of all scenarios arranged up to this point in the sum of the consistency of all scenarios.

Scenario IDs	Additional cost per scenario (€)	Total add, cost (cumulated) (€)	Future space coverage (%)	Consistency	Cumulated Cosistency (%)
7	€1,160,000	€1,160,000	50%	1406	9%
3	€180,000	€1,340,000	80%	1399	18%
1	€300,000	€1,640,000	84%	1433	27%
0	€0	€1,640,000	84%	1411	37%
10	€0	€1,640,000	91%	1397	46%
2	€0	€1,640,000	93%	1381	54%
8	€120,000	€1,760,000	95%	1429	64%
5	€0	€1,760,000	95%	1420	73%
6	€0	€1,760,000	95%	1409	82%
4	€470,000	€2,230,000	100%	1410	91%
9	€0	€2,230,000	100%	1385	100%

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