Approach for Evaluating Changeable Production Systems in a Battery Module Production Use Case

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Abstract. Volatile markets continue to complicate manufacturing companies' production system design, leading to efficiency losses due to imperfect system setups. In such a market environment, a perfect system setup cannot be achieved. Therefore, changeable production systems that cope with immanent uncertainty gain interest in research and industry. For several decades, changeable production systems have been in the research and development stage. The advantages and disadvantages are well investigated. So far, however, they have gained only limited acceptance in industry. One of the reasons is the difficult evaluation of the benefits. Existing investment calculation methods either neglect many effects of changeability, such as easier adaptation to unpredictable events, or are too complex and therefore too time-consuming to become standard. Thus, a practical evaluation method is needed that considers these changeability aspects. This paper deviates the industry requirements regarding an evaluation method based on an industry survey and develops a practical approach for an evaluation method for a changeable production system considering monetary and non-monetary aspects. The approach is characterized by a calculation that is as accurate as possible considering the existing input factors. The method shows that changeable production systems excel in environments with frequent need for adaptation. The approach is applied to a battery module assembly in the ARENA2036 research campus.

Keywords: Changeability · Production system · Evaluation method

1 Introduction

Volatile markets continue to complicate manufacturing companies' production systems design, leading to efficiency losses due to imperfect system setups. In such a market environment, a perfect system setup cannot be achieved. Thus, changeability is required [1–4]. A wide variety of production systems with different levels of changeability has been developed over the last decades [5]. Even though the consideration of changeability in the context of production system design has been sufficiently discussed, assessing

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the optimal level of adaptability is difficult for companies. Different authors analyze the aspects to be considered when deciding on the optimal degree of changeability [6]. Furthermore, they place the aspects in a structural context and describe their interdependencies [1]. Based on these general concepts, different evaluation methods are developed. See Sect. 4. However, based on the cooperation with industrial companies, it can be summarized that these evaluation methods are rarely applied in industrial companies. So far, classical evaluation methods such as the net present value method have been predominantly used, but these systematically disadvantage changeable production systems. Therefore, in the first step an industry survey was conducted in order to detect current obstacles and to elaborate on the requirements for future evaluation methods. Based on this, existing evaluation methods were examined and evaluated with respect to these requirements. Subsequently, a new approach was developed and exemplarily applied in the context of a battery module production.

2 Industry Survey

2.1 Survey Structure

This expert survey is based on the procedures of DIEKMANN [7] and REINECKE [8] and is structured into four parts:

Formulation and Specification of the Research Problem. The aim of this questionnaire was the examination of the current situation of evaluating changeable production systems in manufacturing companies. The research question of this survey can hence be formulated as follows: "To what extent is the optimal degree of changeability for production systems determined in practice?" The formulated hypotheses to answer this research question, including the survey results, are shown in Sect. 2.2.

Planning and Preparation of the Survey. The survey's target group were professionals in the production planning environment in industrial companies and research institutions. Due to the ongoing corona pandemic, this survey was performed via an online tool.

Data Collection. The questionnaire was distributed via e-mail to the target group. The survey participants consist of selected contacts of the research team from the production environment of industrial companies. The questionnaire consists of 15 questions, the most important questions are presented within this paper.

Data Analysis. The goal of the data evaluation is the construction of an analysis-capable data file. The data collection was automated by the survey tool Lime Survey, a manual intervention was not necessary. The "mandatory data" function prevented incomplete questionnaires. An error correction of the data set was therefore not necessary. Twenty-one manufacturing experts from the fields of electrical engineering, automotive engineering, mechanical engineering and IT completed the survey.

2.2 Survey Results

Hypothesis 1: "Changeability is Not Considered When Deciding on New Production Systems".

The survey results show that 79% of the survey participants stated that efforts are made to integrate changeable components into production systems, while 5% even plan new production systems exclusively with changeable components. Therefore, hypothesis 1 cannot be confirmed.

Hypothesis 2: "Evaluation Methods are Used for Investment Decisions Regarding Changeable Production Systems".

To investigate the relevance of evaluation methods in the planning process for changeable production systems, the survey participants were asked about the relevance of different factors on the required changeability. In this context, 57.1% of the survey participants stated "requirements from management" as the decisive factor. This is followed by the orientation on experience reports ("lessons learned") with 47.6%. Other decision factors include orientation towards industry trends with 28.6%. Only one-third of the survey participants said, they use evaluation methods. Consequently, decisions are based on less rational criteria and hypothesis 2 is false.

Hypothesis 3: "Evaluation Methods Do Not Sufficiently Consider All Influencing Variables and Therefore Give Incorrect Recommendations".

To identify deficiencies in general assessment methods for changeable production systems, survey participants were asked about the weaknesses of existing assessment methods. 52.4% of the survey participants think that assessment methods require too many unknown input values. Another 33.3% stated that time-consuming procedures are another deficiency of formal methods, while 14.3% even said that formal evaluation methods do not improve the decision-making process and are not needed. An additional 38.1% of the survey participants stated that evaluation methods inadequately represent the reality or give false investment recommendations. Hypothesis 3 can thus be confirmed.

The survey showed that most participants consider changeability in the planning of new production systems. Evaluation methods exceeding classical approaches are only used sporadically. In addition, most existing evaluation methods are not suitable in practice due to unknown inputs and high complexity. Beyond, survey participants complain that evaluation methods give incorrect recommendations and simultaneously require too many input variables. This shows that there is a need for a method that balances accuracy and usability.

3 State of the Art

Based on the survey and the literature research, five requirements are derived. The possibility of ex ante evaluation is as important as the consideration of all planning phases and the life cycle of the production line. A holistic view of production systems is necessary to consider all influencing factors. To counter uncertainty with changeability, planning uncertainty must also be considered in the evaluation method. To determine the best investment alternative, a consideration of monetary and non-monetary values is necessary.

In the following, the existing approaches from the literature are examined regarding their fulfillment of aforementioned requirements. Möller developed a method for determining the economic efficiency of changeable production systems using the real options theory (see [9]). The real options theory is part of the investment theory and suitable for evaluating changeable production systems under uncertainty. The set of all real options represents the field of action which is available for the decider. Using the net present value method, the individual real options are calculated and compared [10]. Stähr et al. determines the necessary technical measures to achieve the optimal degree of changeability of a production system. The optimality of production systems is determined based on the expected life cycle costs of the production system. The different probabilities of occurring events are determined by Monte Carlo simulation [11]. Heger's Integrative Evaluation of Transformability is subdivided into several analyses: First, it evaluates the potential of a factory object for transfiguration, and second it performs a monetary and a non-monetary analysis. The non-monetary unit of changeability is combined with the monetary valuation, the net present value [12]. Pachow-Frauenhofer approaches the planning and optimization of changeable production systems from a quantitative perspective using control loops and the life cycle costing method. She subdivides the assessment method into goal definition, analysis, design and evaluation. To investigate the optimal degree of changeability, control loops are used to map the change process and to identify necessary dimensions of change [13]. Kluge designs a framework for the basic planning of modular production systems by considering the life cycle costs and the development of a scenario technique [14]. Lübkemann and Nyhuis [15], Schuh et al. [6], Bürgin [16] and Sesterhenn [17] present further approaches considering frameworks for the prediction of future developments or evaluation methods. Due to their different research focus, they are not further elaborated in this paper.

The analysis of existing approaches showed that the following 3 aspects are not adequately addressed: The approaches do not provide an exhaustive list of cost factors. Beyond, most approaches do not consider non-monetary values, while other analyses, such as Heger's [12], tend to result in disproportionately high effort. Furthermore, most authors do not consider all planning phases or the life cycle of the production system. Therefore, the development of an evaluation method that considers all requirements is necessary.

4 Method

Figure 1 depicts the structure of the proposed evaluation method.

1) Changeability Potential Analysis. First, the Changeability Potential Analysis derives different options for the production systems design. The derived options should differ in the investment and operating costs and should have different potentials for changeability.

2) Changeability Profitability Analysis. The Changeability Profitability Analysis considers the options from a monetary perspective. It starts with a scenario analysis and an estimation of the costs and is completed by the monetary comparison. The scenario

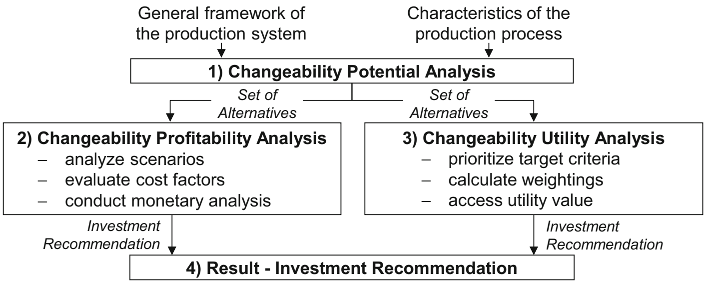

Fig. 1. Structure of the evaluation method

analysis must depict different outcomes and cover the required changeabilities. Therefore, the probability distribution over the different scenarios needs to be assessed. For the evaluation of the scenarios, the respective cost elements must be taken into account. From a cost perspective, two aspects are relevant, which are differentiated according to chronological occurrence: **System design costs** are costs that occur initially before the changeover is required. This enables the system's design to adapt. **System operation costs** describe the costs that occur due to the execution of the changeover. The two types of costs thus represent the total costs of the production system, creating a conflicting relationship. Initial higher changeability costs enable the later more favorable implementation of the changes, thus allowing overall lower total costs and vice versa (see also [1]). An overview of the costs is provided in Fig. 2.

	System design costs	System operation costs
tactical	– Evaluation and planning costs – Acquisition costs – Set-up and start-up costs – Disassembly and disposal costs – Area and inventory costs – Financing costs	– Disassembly and assembly costs – Logistics adjustment costs – Production downtime costs – Additional work costs
operational	– Variable product costs – Plant monitoring and operation costs	

Fig. 2. System design and system operation costs

The individual cost elements result from the combination of different approaches from the literature. The changeability costs consist of all costs related to the acquisition and disposal of a specific production system. The tactical costs are divided into costs for evaluation and planning, acquisition [12], setup and start-up [12], disassembly and disposal [12], area and inventory [15] and financing [13]. The operational costs describe variable product costs (incl. Opportunity costs due to different cycle times) and costs for plant monitoring and operation [14]. The implementation costs arise due to the conversion of the production system. They consist of disassembly and assembly costs for changeover [12], adjustment costs for logistics, production downtime costs [12], additional work costs and investments [14].

Using the scenarios and the cost elements, it is now possible to evaluate the different alternatives. First, the changeability costs $CC_{A,S}$ of the alternative A under a scenario S need to be calculated individually. Then, the expected value E_A of an alternative needs to be deduced.

The changeability costs $CC_{A,S}$ of an alternative A in a scenario S for a period T calculates as:

$$CC_{A,S} = TCC_A + \sum_{t=0}^{\mathrm{T}} (OCC_{A,S,\,\mathrm{t}} + IC_{A,S,\,\mathrm{t}}) \cdot (1 + i)^{-\mathrm{t}} \tag{1}$$

with:

TCC_A	tactical changeability costs of alternative A
$OCC_{A,S,t}$	operational changeability costs of alternative A and scenario S in period t
$IC_{A,S,t}$	implementation costs of alternative A and scenario S in period t
i	discount rate

Based on this, the expected value E_A of an alternative A is calculated as a function of the weighted changeability costs $CC_{A,S}$ of an alternative A in a scenario S:

$$E_A = w_{S_1} \cdot CC_{A,1} + w_{S_2} \cdot CC_{A,2} + w_{S_3} \cdot CC_{A,3} \tag{2}$$

with:

w_S occurrence probability of scenario S

3) Changeability Utility Analysis. Since there are non-monetary aspects that are important to consider as well, the Changeability Utility Analysis takes those aspects into account by using a pairwise-comparison approach. After the prioritization of the target criteria and calculation of the weightings, the partial utility values and thereafter the utility values need to be assessed.

4) Result - Investment Recommendation. Finally, the results of the monetary and non-monetary analysis are combined and an investment recommendation is made.

5 Battery Module Production Use Case

The developed method was exemplarily applied and presented in a use case.

1) Changeability Potential Analysis. Within this project, two alternatives, line production and matrix production, were investigated.

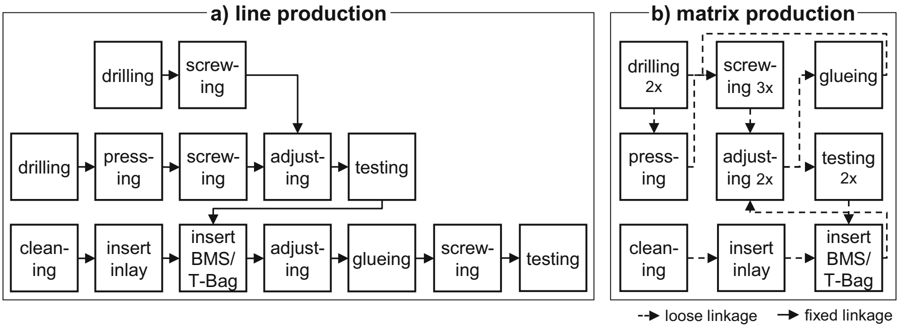

Fig. 3. Production process of line and matrix production

Figure 3 depicts the manufacturing process of a battery module use case in the a) line production and b) matrix production. The line production consists of three independent lines that are merged at different stages. Whereas the matrix production consists of independent stations without fixed linkage that can be operated in different sequences. For a detailed differentiation see also [5]. The cover is drilled and the service connector is screwed to the cover. After the housing is drilled, the four threaded inserts are pressed in, after which a circuit board is screwed to the housing together with a battery holder. The circuit board then is adjusted, and the cover is placed on the housing. Within the final assembly, the cleaned inlays are added to the battery module frame and the pre-assembled battery management system (BMS) is inserted and screwed onto the frame. The T-bag is then screwed into place and the battery module frame closed with a cover, which is glued and screwed to the battery module frame.

2) Changeability Profitability Analysis. In scenario 1 the "pressing"-station must be modified in period 3. Scenario 2 expects the changes in scenario 1 with a required modification of the battery modules in period 4. The assembly is done with an additional bond seam, for which a "bonding" station must be inserted. Scenario 3 combines scenario 1 with a modification of the battery modules in period 4, which requires the addition of two stations, while three stations must be moved. Costs that are identical to both alternatives are not considered. Figure 4. Compares the required changeability qualitatively depending on the scenarios.

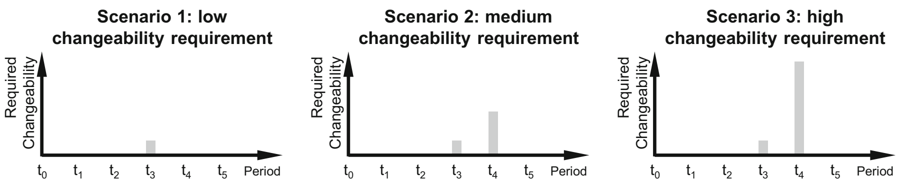

Fig. 4. Scenario analysis

The result of the Changeability Profitability Analysis shows that the matrix production is beneficial for scenarios with high-expected changeability, see Fig. 5. Using formula 2, the expected changeability costs, under consideration of the occurrence probabilities of the scenarios, were € 3.498k for the line production and € 3.229k for the matrix production.

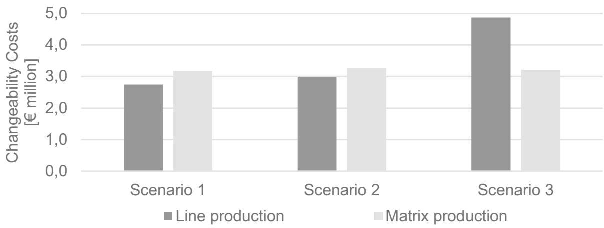

Fig. 5. Changeability costs for line and matrix production per scenario

3) Changeability Utility Analysis. In an expert workshop the two production concepts were compared based on eight criteria, which were evaluated using a scale from 1 (not applicable) to 10 (applicable). Table shows that matrix production excels particularly in process innovation, sustainability and adaption speed (Table 1).

Table 1. Changeability utility analysis

Production system	Weightings	Line production	Matrix production
1. Positive impact on corporate image and culture	12.9%	5	5
2. Increased process innovation rate	16.1%	3	7
3. Better productivity and higher transparency	12.9%	6	4
4. Improved understanding of factory and future space	12.9%	7	5
5. Positive impact on sustainability	12.9%	3	8
6. Higher employee motivation, qualification and retention	12.9%	5	5
7. Increased speed of adaptation and development	19.4%	4	8
Changeability Utility Score		4.6	6.2

4) Result - Investment Recommendation. Since the Changeability Profitability Analysis and the Changeability Utility Analysis both favor matrix production, the matrix production is the favored alternative. As the results show, higher initial investment in the changeability of production systems decreases implementation costs for new conversions. Therefore, changeable production systems do excel in volatile environments and a thorough scenario analysis is crucial to the decision for an optimal degree of changeability.

6 Summary and Outlook

Changeable production systems are a key element of future manufacturing companies. However, the benefits of these production systems are difficult to assess and often depend on the specific application. Therefore, at the beginning of this paper, industry requirements for evaluation methods of changeable production systems were collected and investigated in a structured way by means of a survey. Based on this, specific requirements were formulated and relevant methods from the literature were compared with these requirements. The existing assessment approaches have shown that a pragmatic approach for assessing the necessary changeability does not exist. They are either not accurate enough or the methods require excessive data. This paper therefore develops an evaluation method and applies it to a battery module assembly use case in the ARENA2036 research campus. The presented method combines a pragmatic and practice-oriented approach for evaluating changeable production systems by combining and extending existing approaches. The approach is characterized by a calculation that is as accurate as possible, considering the existing input factors and thus serves as a first step towards more data-driven decision-making regarding changeable production systems.

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