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Evaluation of factory elements for the configuration of learning factories

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Abstract

Learning factories for lean production represent the majority of the learning factories worldwide. Learning factories for lean production represent the majority of them. For the design of learning factories, the organisational framework, the organisational targets, the target groups and the intended competencies should be clarified, so factory elements can be preselected. Examples of factory elements in learning factories are machines, equipment, assembly lines or logistics systems. The selection of factory elements is a complex task since various restrictions must be considered such as the budget or layout constraints. Configuration systems can simplify the selection process. Since the learning factory developer wants to choose the best factory elements, it is necessary to define how to evaluate the utility of the preselected factory elements. Both competency-based criteria based on the learning targets, and general evaluation criteria for learning factories such as the degree of changeability play a role. In this paper, an evaluation method is presented which allows an individual evaluation of factory elements for learning factories with the focus on lean production. The method is based on a utility value analysis with previously researched evaluation criteria. For each evaluation criterion, a fixed classification is made into strong, medium, weak and non-evaluable. Since the evaluation criteria are different for each learning factory, they can be weighted individually according to the specific use case. This evaluation scheme can also be used to evaluate existing learning factory configurations. As a case study, factory elements of the process learning factory CiP of the TU Darmstadt are examined. However, new learning factories to be developed can also be configured on this basis.

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Keywords: Factory Design; Factory Elements; Evaluation Method; Lean Production

1. Introduction

The development of competences takes on a crucial role in meeting the challenges in companies [1]. Learning factories have established themselves as an effective form of competency development [2]. More and more universities and companies decide to use a learning factory approach. Learning factories offer learning environments that allow learning in an interactive scenario within a realistic production system [3]. The wide distribution of learning factories highlights the importance of the configuration process of learning factories. In addition to the operating model and the didactical concept with intended competences and learning methods, the socio-technical infrastructure should be specified [4]. One of the decisions to be made is to select the combination of factory elements that have the highest utility and respect certain restrictions, such as the available budget. The procurement of factory elements is a cost-intensive aspect that determines the future possibilities in learning factories. However, no method exists yet to systematically evaluate and select factory elements in learning factories. This paper addresses this research gap with an evaluation method for factory elements in learning factories. After the basics of learning factory design are described in chapter 2, an evaluation method for factory elements is presented in chapter 3. The utility analysis is used as a foundation, which is further detailed and operationalized for the design of learning factories. Chapter 4 describes a use case with evaluated factory elements at the process learning factory “Center for industrial productivity” of the Technical University Darmstadt. The results are summarized with an outlook in chapter 5.

2. Basics

With an increasing number of learning factories that are established worldwide, it gets more important to design this process as goal-oriented and systematic as possible. To develop learning factories, the integrated learning and factory perspective should be adopted [5]: The learning factory is seen both as a complex learning environment and as a realistic representation of a factory. This leads to technical, didactical and organizational implications for the design of learning factories. Intended competencies or learning goals are derived from the organizational framework, the organizational goals and the target groups. Both the didactic infrastructure and the technical system are based on these intended competencies and training scenarios. More precisely, intended competencies and possible trainings scenarios pose requirements to the socio-technical infrastructure [4].

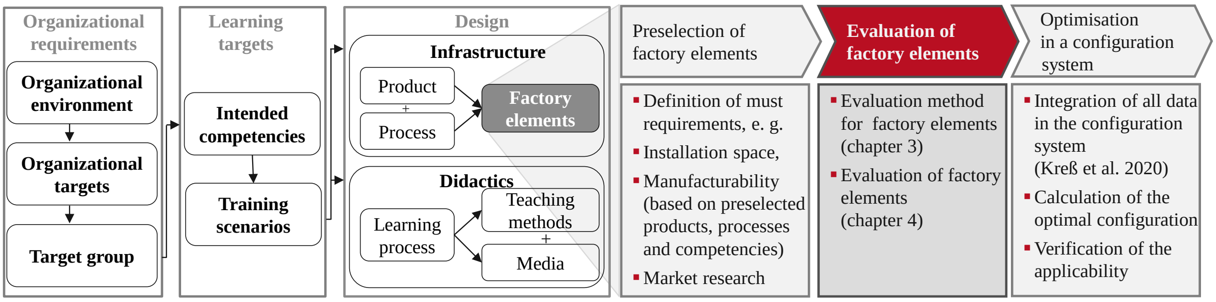
Multiple options and alternatives for factory elements are usually available to choose from. The selection of specific factory elements for the technical configuration of learning factories is usually instinctive and experience based. Optimal solutions are usually found only by chance. A configuration system for learning factories supports the configuration process [6]. For this purpose, factory elements must first be researched and preselected, which are then evaluated and integrated into the system (Figure 1). There is no procedure for the evaluation of factory elements in learning factories yet. For this paper factory areas and factory elements are defined as follows:

- **Definition 1: Factory areas** represent segments in factories that are required directly or indirectly for the value creation. Factory areas are derived from a (future) value stream of the used product.

- **Definition 2: Factory elements** represent specific operating equipment for the value creation in factory areas. Factory elements enable realistic processes to be mapped in learning factories. Examples for factory elements are milling machines, assembly lines, logistics systems etc.

In a next step, the best possible factory elements can be selected by the configuration system (depending on the given requirements, such as the available budget and the usable area for the learning factory). Each individual factory element has a specific utility, but also requires resources (e.g., through area and costs). Finding the best possible combination of factory elements is not trivial. Therefore, an optimization problem is solved that maximizes the overall utility of all chosen factory elements while respecting several resource restrictions. This optimisation problem is modelled by a multidimensional multiple choice knapsack problem (MMKP) combined with a two-dimensional packing problem [7]. For each factory area, the MMKP selects one alternative that contains one or more factory elements. If the factory area is optional, this alternative can consist of an empty element (with no resource consumption). Several products can be considered by applying the optimization problem for each product and using the configuration with the highest overall utility. Another key aspect when applying an optimization problem is that it ensures an optimal solution, which otherwise would not be possible. While no method exists yet to evaluate factory elements for learning factories, the underlying research question of this paper is how to measure the utility value of individual factory elements for learning factories.

Fig. 1: Selection process for factory elements based on the design for learning factories (based on [4]).



3. Evaluation method for factory elements

3.1. Requirements for the evaluation method

To develop an evaluation method for factory elements in learning factories that is as **generalisable** as possible, different requirements should be considered for the design of the method. The evaluation itself should be as **objective** as possible. This means that the evaluation criteria should contain variables that are as objectively measurable as possible. Different persons should come to the same outcome when applying the method. The evaluation method should be **flexible** and **expandable**, as learning factories will continue to evolve in the future. Based on the use case, the weighting of the individual criteria can be carried out individually by the potential learning factory operator. Further evaluation criteria can be added over time. The evaluation should be as **complete** as possible and thus reflect as many aspects and a minimum of complexity for the configuration of learning factories as possible. Nevertheless, the method should be **easy to apply**, and the scope of the method should be appropriate. The individual assessment criteria should also be **free of redundancy**, otherwise they would be over- or underrepresented and the assessment would be distorted.

3.2. Structure of the evaluation method

The structure of the evaluation method is based on a utility value analysis [8]. The utility analysis is often used for factory planning and is particularly suitable due to its simple application. In total, J factory areas with I factory elements each are to be evaluated for each learning factory. To calculate a utility value u_{ij} for the target function U, K different evaluation criteria are considered. Two steps are necessary here: weighting the evaluation criteria (w_k) and evaluating the factory elements for each criterion (e_{ijk}). The **weighting of the criteria** (step I) can be done by a pair comparison [9] in which each criterion is compared with each other and statements are made whether the first criterion is more important (indicated with 2), equally important (indicated with 1) or less important (indicated with 0). Through summation and scaling, a differentiated weighting result. Besides the pair comparison, it is possible to directly influence the weighting by assigning numbers from 1 (very unimportant) to 10 (very important) to each evaluation criterion k. In the second step, the **evaluation** of the preselected factory elements by each evaluation criterion is carried out (step II). Each evaluation criteria can be expressed by the classification "non", "weak", "moderate" and "strong". This classification is detailed by operationalizing the evaluation criteria with specific variables [10]. The information for the evaluation of the factory element can be taken either from product catalogues or by manufacturer requests. For each criterion, it must be defined from which variable value it falls into the evaluation categories "non" to "strong". To highlight differences between the factory elements, the factory elements should be distributed as heterogeneously as possible in the evaluation categories. Since the potential factory elements depend on the use case, the corresponding variable values for classification into the evaluation criteria also depend on the use case. To calculate a weighted utility value u_{ij}, numbers are defined for the classifications (from "non" to "strong"). In the simplest case, the numbers are equally distributed (e.g., 0 for non - 3 for weak – 6 for moderate - 9 for strong). For each factory element i of the factory area j, a utility value u_{ij} results from the sum product of the weighting for the criterion w_k and the evaluation for each criterion e_{ijk} according to the formula (1). The utility values are used to calculate the target function U in formula (2), in which the binary variable x_{ij} indicates if a factory element will be selected for the learning factory. In a next step, this utility value is used in an optimisation problem that selects the combination with the highest overall utility subject to further restrictions of the formulae (3) and (4).

$$u_{ij} = \sum_{k=1}^{K} w_k \cdot e_{ijk} \qquad (1)$$

$$U = \sum_{j=1}^{J} \sum_{i=1}^{I} u_{ij} \cdot x_{ij} \qquad (2)$$

$$\sum_{j=1}^{J} \sum_{i=1}^{I} w_{ijk} \cdot x_{ij} \leq C_k \qquad (3)$$

$$\sum_{j=1}^{J} x_{ij} = 1 \qquad (4)$$

3.3. Evaluation criteria

A literature review and expert interviews with researcher in the field of learning factories and employees of a company (that is in the designing phase of a learning factory) were conducted to derive the evaluation criteria. For this purpose, the databases ScienceDirect and Google Scholar were searched for literature containing possible evaluation criteria for factory elements in learning factories. The researched evaluation criteria were filtered. The evaluation criteria of this paper focus on learning factories for lean production, in which technical-methodical competencies for lean methods can be developed. Table 1 gives an overview of the evaluation criteria, which are explained in the following.

- **C1: Interaction capability**
  Active learning as an important part of activities in learning factories is made possible by interacting with factory elements [11]. Factory elements for learning factories with focus on further education and teaching should be as interactive as possible. For this purpose, a list of competency-based interactions should be derived from the intended competencies. The more competence-based interactions a factory element can carry out, the higher the utility of the factory element. In learning factories for lean production, the intended competencies are derived from lean methods. Examples for interactions are moving a workplace to improve the factory layout, organizing tools to implement 5S, measuring times for a yamazumi diagram, collecting process data for a value stream analysis etc. The relationship between lean methods and interactions can be shown in a matrix. If a certain interaction with a factory element is necessary to learn a lean method, the interaction is counted. Interactions should be described in detail for this evaluation. The sum of competency-based interactions indicates a higher interaction possibility. For this purpose, values were defined for the number of interaction possibilities, with which the factory elements can be divided into strong, moderate, weak and non.
- **C2: Implementation of design principles**
  The design principles of lean production should be implemented in learning factories for lean production. In this way, the learning factory can serve as a best practice and thus motivates the training participants to implement them in the company [12]. In this paper, the design principles of VDI 2870 were used [13]. These include avoidance of waste, standardisation, continuous improvement, zero defect principle, flow principle, pull principle, employee orientation and leadership, as well as visual management.
- **C3: Integrability of errors and waste**
  Problem-oriented learning becomes possible by integrating errors and waste (C3) in the production process [14]. The learners can learn to see waste. With an increasing number of integrated errors and types of waste, the utility increases as well.
- **C4: Closeness to reality**
  The transfer of what has been learned into practice increases with the closeness to reality of the factory elements [15]. This is an important advantages of learning factories. Factory elements are closer to reality the more they are used in the actual production environment.
- **C5: Use of digital technologies**
  More and more learning factories are using digital technologies to (1) train new content on these technologies or (2) improve the learning processes during training. The opportunities for learning factory operators increase with the number of technologies used in factory elements [16, 17]. For this purpose, a list of technologies has been created to facilitate the evaluation. Examples for digital technologies are 5G, artificial intelligence, RFID, assistance systems etc.
- **C6: Actuality**
  Many learning factories would also like to show the most recent factory elements in order to present a current state of research. The variable considered for the criterion actuality is the year of market launch. It should be noted that this criterion conflicts with the criterion "closeness to reality" since very current factory elements are usually not yet widely used.
- **C7-11: Changeability**
  Changing environmental factors influence learning factories, which should be as changeable as possible [19]. According to Wiendahl [20], five drivers of changeability are defined: universality (C7), modularity (C8), mobility (C9), compatibility (C10) and scalability (C11). These are individually evaluated in the evaluation system. Universality increases with adaptability to an increasing number of different requirements; modularity with the number of standardized and independent components; mobility with decreasing movement effort; compatibility with the number of possibilities for connectivity; and scalability with the number of possibilities for expandability and reproducibility.
- **C12: Sustainability**
  Sustainability plays a major role for manufacturing and learning factories [21]. Factory elements with low resource consumption in different categories obtain a better rating. For the evaluation, a comparison between all potential factory elements must be considered.
- **C13: Preparation effort**
  In addition, the preparation effort for training and demonstrations should be minimal. Factory elements whose effort is low, e.g., due to low maintenance requirements, perform correspondingly better at this criterion.

Table 1: List of evaluation criteria.

#	Evaluation criterion	Variable / Description
C1	Interaction capability	Number of competence-based interactions with the factory element
C2	Implementation of design principles	Number of implemented design principles of lean production systems
C3	Integrability of errors and waste	Number of integrable errors
C4	Closeness to reality	Frequency of use of the factory element in operational practice
C5	Use of digital technologies	Number of digital technologies used
C6	Actuality	Year of market launch for the factory element
C7	Universality	Adaptability with regard to different requirements
C8	Modularity	Number of standardised and functional elements
C9	Mobility	Degree of mobility
C10	Compatibility	Number of connectivity options
C11	Scalability	Number of possibilities for expandability and reproducibility
C12	Sustainability	Resource consumption of the factory element
C13	Preparation effort	Estimated time needed to prepare for a learning module and to maintain it

Before the method can be applied, the corresponding variables should be operationalized to the use case. E.g., the number of digital technologies must be adjusted. The values of the variables for the classification into "non", "weak", "moderate" and "strong" depend on the learning factory to be developed and should be adjusted accordingly after the pre-selection of the factory elements. When distributing the values, attention should be paid to the respective maximum and minimum values so that the evaluation can be distinguished as well as possible.

4. Results of the evaluation

The method for evaluating factory elements was applied to J=10 factory areas, each with I=5 factory elements, in a case study at the process learning factory “Center for industrial productivity” (CiP) of the Technical University Darmstadt. Excluding empty factory elements for optional factory areas, 45 factory elements were evaluated. First, possible factory elements were researched and preselected with the help of must requirements (e.g., manufacturability). The classification into factory areas was done based on a value stream analysis. Subsequently, the researched evaluation criteria were operationalised as described, i.e., it was determined which value range of the variables belonged to "non", "weak", "moderate" and "strong". In addition, the evaluation criteria were weighted in a team of experts with the help of the pairwise comparison. By collecting data in data sheets, the values of the variables could be determined. The result for the factory area sawing is depicted in Table 2. The rows contain the preselected factory elements. It should be mentioned that the original names for the factory elements were changed for this work so that no manufacturers were named. Nevertheless, there are specific sawing machines behind these names that can be bought. The columns contain the evaluation criteria with the corresponding ratings. While there are big differences between the factory elements in some criteria (e.g., C1: interaction capability), the factory elements do not differ in other criteria (e.g., C9: mobility). Based on the weighting, the manual sawing machine has the highest utility because, for example, many interactions are possible, which is not the case with a fully automatic saw. For other weightings of the evaluation criteria, the result can be significantly different. In the next step, the configuration system with the optimization problem should be applied as described in chapter 2. Whether the factory element with the highest utility value is selected ($x_{ij} = 1$) also depends on the restrictions (e.g., by the available budget or the dimensions of the learning factory). To solve this optimization problem an appropriate algorithm should be chosen (e.g., in [7]).

Table 2: Use case for the evaluation method.

Factory area	Preselected factory elements	C1: Interaction capability	C2: Implementation of design principles	C3: Integrability of errors and waste	C4: Closeness to reality	C5: Use of digital technologies	C6: Actuality	C7: Universality	C8: Modularity	C9: Mobility	C10: Compatibility	C11: Scalability	C12: Sustainability	C13: Preparation effort	$\frac{u_{ij}}{u_{max}}$
	Weight	**10**	**10**	**7**	**9**	**9**	**3**	**7**	**4**	**7**	**7**	**5**	**4**	**6**	
Sawing	Double mitre machine	◔	●	◔	◕	◔	●	◕	◔	◔	◔	◔	◔	◔	85.5 %
	Fully automatic sawing machine	○	●	◔	◕	◔	●	◕	◔	◔	◔	◔	◔	◔	78.9 %
	Semi-automatic sawing machine	◔	●	◔	◕	○	●	◕	◔	◔	◔	◔	◕	◕	86.2 %
	Manual sawing machine	◕	●	◕	◕	○	◕	●	◔	◔	◔	◔	◕	◕	100.0%
…															

Legend	● Strong: 9	◕ Moderat: 6	◔ Weak: 3	○ Non: 0

5. Conclusion and outlook

In this paper a method was presented with which factory elements for learning factories can be evaluated. The structure of the method was derived from requirements for the evaluation of factory elements. The utility value analysis forms the basis for the evaluation, as it is widely used in factory planning and is easy to apply. In total, 13 evaluation criteria were derived from the literature, e.g., interaction capability and closeness to reality. Each identified criterion has also been operationalised so that it can be objectively measured. The criteria are to be weighted individually depending on the use case, for which a pair comparison is useful, for example. The evaluation method was exemplarily applied in the process learning factory CiP in the factory area sawing. The decision which factory elements should be selected can be supported by the presented method – for both planning new or reconfiguring existing learning factories. Since budget and area restrictions usually do not allow the selection of all factory elements with the highest total utility value, a configuration system based on an optimisation problem provides additional support [6]. For a practical use, the configuration system should be available as an open-source solution. It is planned that the evaluation method will be applied in further learning factory projects (e.g., in [22]). For this purpose, adjustments are necessary in each use case such as the value range for variables or the weighting of the evaluation criteria. While this paper focuses on learning factories for lean production, further research is needed for other competence areas such as energy and resource efficiency [21]. While some evaluation criteria are not dependent on the intended competences (e.g., C4 closeness to reality), others change with the learning content (e.g., C1 interaction capability). During the application it has been shown that the weighting of the evaluation criteria depends on the primary targets of the learning factory (research, teaching and training). To simplify the process, the weighting could be predefined for each primary target.

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