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System development for the configuration of learning factories

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Abstract

Learning factories represent realistic learning environments for academia and industry in order to develop competencies. The design of learning factories can be facilitated by a configuration system. The configuration of a learning factory describes the selection of factory elements and products. Mathematically this selection can be described by an optimization problem based on a utility function and restrictions. Optimization algorithms facilitate the planning process by selecting the feasible combination of factory elements with the highest utility. This paper describes the methodology to develop a configuration system for learning factories. Customer needs for the configuration system were identified by an explorative stakeholder study: Learning factory developers, operators, and trainers were interviewed with open and partially open questions. These customer needs were then evaluated regarding their importance. The relationship between customer needs and functional requirements is described in a House of quality. To determine the system design systematically, the decomposition principle and the zig-zag process of the Axiomatic Design were applied. Axiomatic Design is a method to design engineering systems including complex systems and software. Consequently, the functional requirements were transformed into design parameters. Design parameters characterize the design of the configuration system.

Keywords: Learning Factory; Factory Design; Axiomic Design; System Development; House of Quality

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1. Introduction

Increasing requirements for companies, such as new technologies, shortening product life cycles or demographic change, demand more and changing competencies from employees [1]. According to the knowledge-based view, competencies represent the most important resources of a company in order to remain competitive on the market [2]. Learning activities that are not action-oriented are not sufficient to develop competencies that focus on actions. For this reason, more and more learning factories have been built in recent years in which employees and students are able to learn in realistic production environments [3]. The design process of learning factories differs significantly from conventional factories, as the focus is on the development of intended competencies [4]. The construction of learning factories is associated with high capital expenditure. Therefore, a learning factory design should be well considered. A quantitative optimization model, in which the best possible combination of factory elements is selected, would simplify the design process. Quantitative optimizations provide fast and more objective results. However, such a system does not yet exist. The aim of this research paper is to describe a methodology to develop a configuration system for learning factories. After the most important basics and terms for the configuration of learning factories have been clarified in section 2, section 3 deals with an explorative stakeholder survey to determine the requirements for a configuration system. The methodology of system development is then presented in section 4. Therefore, This paper combines a stakeholder with a House of Quality [5] and the engineering method Axiomatic Design [6]. While the House of Quality focuses on the relationship between stakeholder needs and technical requirements, the Axiomatic Design regards the relation between the functional requirements and the system design. Section 5 ends with a short conclusion.

2. Configuration of learning factories

In order to design learning factories, three design levels are considered [7]: The macro level considers the technical infrastructure of the learning factory as well as the curriculum; the meso level focuses on individual learning modules; and the micro level considers individual teaching-learning situations. Learning factories should be designed based on intended competencies. In order to design a learning factory, the organizational environment of the future learning factory operator is first considered (see Fig. 1) [8]. Learning factory operators are usually universities, manufacturing or consulting companies. Based on this, the organizational targets with regard to the learning factory are analyzed. Organizational targets for companies include quality, costs, time, flexibility, security. For universities, organizational targets are derived from research, training, and teaching. By defining the target group, the intended competencies can then be inferred. Competencies are human dispositions to react creatively to changing conditions through independent action and reflection [9]. An example of an intended competency from the field of lean production is the performance of a value stream analysis in an unknown production environment. To design the infrastructure and the didactics, training scenarios should be described based on the intended competencies. The description of possible training scenarios gives the learning factory developer a concrete idea and thus simplifies the next steps. The configuration of a learning factory considers the selection of factory elements for the technical infrastructure based on the chosen product for the learning factory and the process to manufacture this product [10].

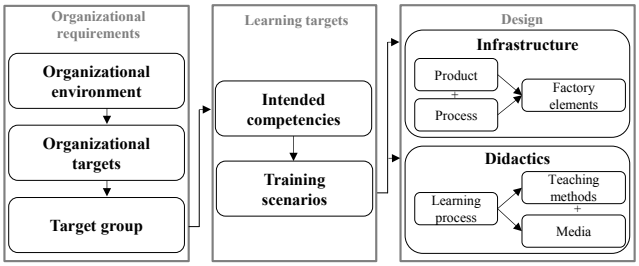

Fig. 1. Design of a learning factory [7,11].

The used product and processes should be aligned with the organizational requirements. In most cases, the product is chosen first, but it is also possible to define processes first and derive a product. Examples of factory elements are different machines, workstations or assembly lines that are used in the learning factory. Each factory element has a utility for the learning factory based on the organizational requirements and the intended competencies. The target of a configuration system is to find the combination of factory elements that represents the highest possible utility. However, there are some restrictions that need to be considered, such as the available budget or the area of the learning factory. To find the optimal combination an optimization algorithm can be used [8,12].

3. Stakeholder needs for the configuration system

Involving stakeholder needs in the design process of systems is important to increase their satisfaction [13]. To determine stakeholder needs for a configuration system, a two-stage survey was conducted. The first step of the study is to identify possible stakeholders [14, 15]. Stakeholders for the configuration system are primarily learning factory developers and secondary learning factory operators and trainers. For this study, 11 stakeholders have been questioned. In the first stage of the study, the study participants were asked in the following question groups, what needs they have of a configuration system with openly asked questions:

i What input variables should be included in a configuration system for learning factories?
ii What functions should be included in a configuration system for learning factories?
iii What should be shown in the result?
iv What are the additional requirements for a configuration system for learning factories?

For the stakeholder study, the goal of a configuration system was first explained in more detail. After all study participants had been interviewed, the answers were summarized. The summary is necessary because different study participants name the same stakeholder needs differently. In the second stage, the final list of all needs was assessed by all stakeholders in two different ways. First, the participants should assess the needs on a scale of 1 (not important at all) to 5 (very important). Since this type of survey often results in many stakeholder needs being evaluated with a high to very high importance, an additional fixed-sum question was added [16]. The participants were asked to allocate a fixed amount of points for the stakeholder needs. More points for one need in a question group results in fewer points for another. Therefore, the participants have to make a trade-off.

Group	Stakeholder needs	Average rating	
		Importance	Fixed sum question
i. Input variables	i.1 Budget for the learning factory		
	i.2 Measurements of the learning factory		
	i.3 Intended competencies		
	i.4 Number of trainers		
	i.5 Number of participants		
	…		
ii. Functions	ii.1 Calculation of the optimal factory design		
	ii.2 Calculation of the optimal product		
	ii.3 Review of the own learning factory design		
	…		
iii. Results	iii.1 Cost analysis		
	iii.2 Layout planning		
	iii.3 Competencies that can be trained		
	…		
iv. Additional requirements	iv.1 Usability of the system		
	…		

Fig. 2. Extract of the stakeholder study.

The cognitive load is relatively high when assigning the exact number of points, so digital assistance was given. Since input variables cannot be compared with functions or the representation of the result, each of the above questions (i to iv) has an own predetermined number of points to be assigned. This number depends on the total number of stakeholder needs times 10, e.g. 140 points for 14 stakeholder needs in the question category "input variable". This evaluation is part of the House of Quality (section 4) and helps to distinguish important from unimportant needs during system development [17]. Fig. 2 shows an extract of the result of the stakeholder study.

The stakeholder needs are listed for each question category (i to iv) with the average relative importance. In order to compare the stakeholder needs for the fixed sum question, the average points assigned for each question category (i to iv) were divided by the respective maximum. The given answers of the interviewed stakeholders in the first stage are very similar. The most important input variables are the intended competencies, the budget, and measurements of the learning factory. Furthermore, the number of trainers and participants also determines the configuration of the learning factory. A small trainer capacity means that fewer training sessions can be offered, which limits the number of factory areas used. The most important function is the calculation of the optimal design. This justifies the use of a mathematical optimization problem. The result should include a cost analysis of the selected factory elements. For further support, the factory layout and the intended competencies that can be trained should also be displayed in the result. In addition, the configuration system should have a high degree of usability. For this reason, usability tests should be carried out at a later stage of the project.

4. System development methodology

System development represents the process of defining, designing, testing and implementing new systems. A system consists of interrelated elements that influence each other and serve a purpose [18]. Many methodologies exist to develop systems. The regarded system of this paper is the configuration process for learning factories. The choice of a methodology depends on the kind of system that should be developed. To develop a configuration system for learning factories this paper uses a combination of two widely used methodologies: the House of Quality [5] and Axiomatic Design [6]. The House of Quality as a part of the Quality Function Deployment (QFD) is a product development technique to translate customer needs to technical requirements. In this paper stakeholder needs are regarded instead of customer needs to consider various perspectives that are identified and assessed in the stakeholder study [19]. Fig. 3 shows an extract of the House of Quality.

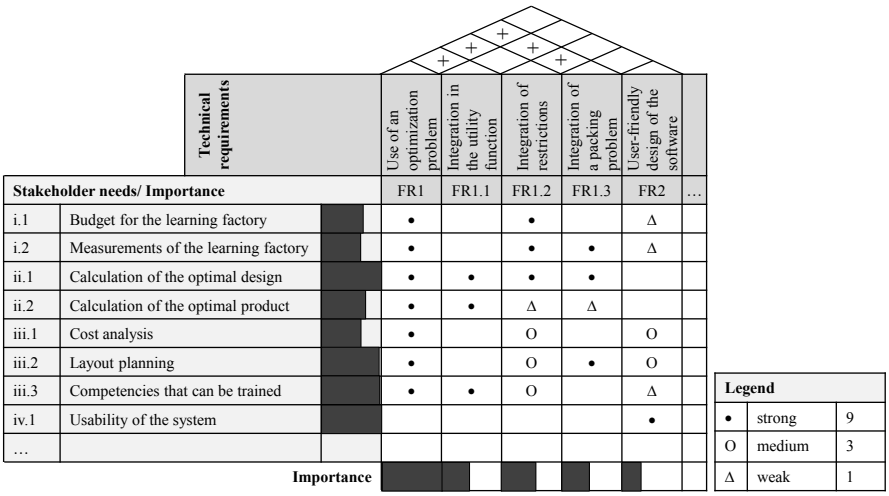

Fig. 3. House of quality for the configuration of learning factories.

The roof of the House of Quality represents the correlation between technical requirements. The technical requirements and their relationships to each other and to the stakeholder needs were derived deductively while considering further elements of learning factories [3]. The most important functional requirements can be identified based on the assessment in the relationship matrix, e.g. “the use of an optimization problem”. Since no configuration system for learning factories has been developed so far, a competitive assessment has not been conducted in this paper.

Many QFD experts stated that QFD is not useful for the creation of new products, because the identified needs in the House of Quality do not focus on the architecture of the product [20]. Therefore, the method Axiomatic Design is used additionally by different authors [21]. Axiomatic Design was introduced in the mid-1970s as an engineering method to establish a theoretical basis and to structure the design process [22]. The method is based on two axioms for good designs. The first axiom states that functional requirements should always be independent (independence axiom). To avoid complex designs the information content of the design should be minimal (information axiom). Four domains are considered in the design process itself (see Fig. 4). The customer domain contains the customer or stakeholder needs of the House of Quality; the functional domain contains the functional requirements FR (e.g. outputs, specifications of the configuration system), the physical domain contains design parameters DP (e.g. optimization algorithms and input variables) and the process domain contains process variables (e.g. subroutines in a software code). The relation between each domain is represented by vectors and matrixes, for example between the functional and the physical domain in equation (1), where n is the total number of the functional requirements FR, m is the total number of design parameter DP and the matrix entries A_{ij} are either X or empty [23]:

$$\begin{pmatrix} FR_1 \\ \dots \\ FR_n \end{pmatrix} = \begin{pmatrix} A_{11} & \dots & A_{1n} \\ \vdots & \ddots & \vdots \\ A_{m1} & \dots & A_{mn} \end{pmatrix} \begin{pmatrix} DP_1 \\ \dots \\ DP_m \end{pmatrix} \tag{1}$$

The functional requirements FR are mapped against design parameters DP with the help of a design matrix A that characterizes the system's design. Design parameters represent how the functional requirements are implemented in the system. The decomposition principle states that the different variables in the four domains are subdivided until the design can be implemented without further decomposition. The decomposition of these vectors is done through zig-zagging between the domains (see Fig. 4): in a first step design parameters are derived from functional requirements; then functional requirements are subdivided based on the design parameter.

In order to fulfill the independence axiom, the design matrix A should be uncoupled, i.e. represent an identity matrix [22]. Each FR is implemented by a DP and thus interrelationships are avoided, that cause complex designs. If an uncoupled matrix is not possible, a decoupled matrix should be used. With a decoupled design, the transformation of the FR to DP is not completely independent: a certain sequence must be followed. This means that the design matrix A is a triangular matrix. All other forms are coupled designs that should be avoided because user input results in an undefined and complex output. The matrix used in Axiomatic Design is different from the matrix used in the House of Quality because it considers the product or system design for the zig-zagging process. The process domain is not included in this paper since the physical domain with the system design is focused.

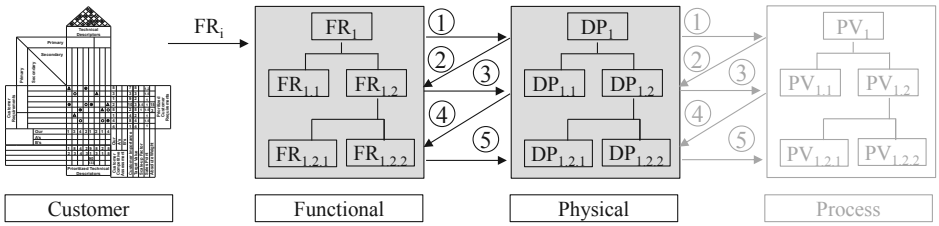

Fig. 4. Four domains and zig-zag process of the method Axiomatic Design.

The deductively derived design parameters DP represent algorithm modules and input variables for the configuration of learning factories. Intended competencies are input factors that are used for the assessment of factory elements. An essential algorithm module is the optimization algorithm to solve the optimization problem which can be represented by a combination of a knapsack problem with an integrated bin packing problem to calculate a factory layout. While the knapsack problem focuses on the selection of factory elements without considering the specific measurements, the bin packing problem offers more restrictions to consider these measurements [10].

5. Conclusions and outlook

This paper focused on the development process of a configuration system for learning factories. The configuration system transforms user input with the help of algorithms. Based on a stakeholder survey, systems requirements are identified and assessed. Input factors should be i.e. the available budget, measurements of the learning factory and the intended competencies. The result includes a cost analysis, layout planning, and competencies that can be trained. The development methodology is a combination of the House of Quality and Axiomatic Design. Stakeholder needs are transformed into functional requirements. The most important functional requirement is the use of an optimization problem that is able to select the optimal combination of factory elements and the optimal selection of a product. While this approach sets the initial design, next versions are developed iteratively through testing and implementing.

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