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Revision of the Learning Factory Morphology

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Abstract

Since its first publication in 2015, the learning factory morphology has been frequently used to design new learning factories and to classify existing ones. The structuring supports the concretization of ideas and promotes exchange between stakeholders. However, since the implementation of the first learning factories, the learning factory concept has constantly evolved. Therefore, in the Working Group "Learning Factory Design" of the International Association of Learning Factories, the existing morphology has been revised and extended based on an analysis of the trends observed in the evolution of learning factory concepts. On the one hand, new design elements were complemented to the previous seven design dimensions, and on the other hand, new design dimensions were added. The revised version of the morphology thus provides even more targeted support in the design of new learning factories in the future.

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1. Introduction

Learning factories (LFs) can be designed in a variety of ways depending on the learning and research objectives [1, 2]. This diversity poses a challenge during the design phase. Thus, a morphology was developed by the CIRP Collaborative Working Group on “Learning Factories for future oriented research and education in manufacturing” in 2015, which shows possible characteristics for the individual design elements [3]. This morphology represented the first multidimensional description model for learning factories and shows the broad variety of LFs. However, since then, the LF concept has evolved, and a systematic adaptation of the morphology is necessary to support the design of future LFs. A major objective of this paper is the revision and extension of the existing morphology for LFs. The associated research question details this goal: *Through which design dimensions and elements should the existing morphology for LFs be expanded?*

2. Methodology

2.1. Research Design

The extended morphology is based on the multidimensional framework first proposed by Tisch et al. (2015) which includes seven dimensions and was introduced as a starting point for the structuring and classification of

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LFs [3]. Since then, many LFs have been developed worldwide and the LF concept has evolved. Therefore, the goal of the Working Group "Learning Factory Design" of the International Association of Learning Factories (IALF) is to standardize and to give guidance to the design process for LF. One of the first steps of the design process is the application of the LF morphology. Based on the published literature on LFs since then as well as on the experiences of the members of the Working Group further design dimensions, design elements as well as possible characteristics are added. The mixed method approach was chosen as the research design: Multiple brainstorming meetings with a benchmarking analysis based on a literature survey were held. The mixed methods research is the process of utilizing two or more methods to meet the aim of a study [4]. It involves collecting, analyzing, and mixing data types within one study. In the benchmark market analysis [5], standards of current LFs [1] were considered. The morphology is also published in the book “Learning Factories” [1], the best practice examples of the LFs from the same book were not yet taken into account, as the morphology was created in 2015 before the book was published in 2019. Previous publications at the Conference on Learning Factories were used as literature. The expert experiences of the Working Group members are characterized by different views on LFs regarding previously designed and improved LFs for industry and academia were collected, analyzed, structed according to the dimensions of the morphology, and reconciled with the findings of the literature analyses. Therefore, the revision of the morphology includes on the one hand the experience of the elaboration of the original version published in 2015 [3] as well as the expertise of six different universities currently operating LFs within their facilities that have also contributed to the establishment and design of new LFs making use of the previous morphology.

2.2. Criteria for new design element

Before adding new design elements, the following criteria were verified:

- **Consideration of the definition of LFs**
  The previous definition of LFs stated minimum requirements that should be considered when formulating new design elements.
- **Coherence to the existing morphology**
  When adding new design elements, on the one hand, the structure of the previous morphology was respected. On the other hand, it was checked whether similar elements are already included and how they are related.
- **Relevance for the objective of the morphology**
  The new design elements should influence the design of LFs. In the previous morphology, considerations were still missing, which, however, are important for the design of LFs and should not be forgotten.
- **Consideration of new topics in LFs**
  Learning and research content in LFs has changed significantly in recent years. The new topics (such as from the field of digitalization, sustainability, and circular economy) should therefore be taken into account.
- **Applicability to international organizations**
  The characteristics of the criteria should take into account international systems and terms instead of being specific to individual countries, e. g. when specifying the target group.
- **Appropriate level of detail**
  The new design elements should be neither too detailed nor too general but adapted to the purpose of the morphology (the design of LFs). An appropriate level of detail is crucial to ensure that the design elements effectively capture the relevant concepts and processes. The design should strike a balance between being too specific, which may limit the scope of the morphology, and being too general, which may fail to capture important nuances of the LF design.

3. Results of the Revision

3.1. Overview

The results are specifically new design dimensions, new design elements as well as new possible expressions in a revised version of the LF morphology. In this way, all relevant and generally applicable aspects are considered in the design of LFs based on the experience of the experts.

Following the framework established by the previous version of the morphology [3], the revised version is structured into design dimensions for the definition for LFs. In the existing design dimensions, new design elements and new characteristics have been added. Table 1 shows the number of added design elements and characteristics to the existing design dimensions. Furthermore, one new design dimensions has been added. In

Table 1 the new design dimension is underlined. In total, 30 new design elements and 203 characteristics have been added. The complete morphology is available at the resource section of the IALF homepage.

Table 1. Number of added design elements and characteristics.

Design dimension	No. of added design elements	No. of added characteristics …in new design elements	…in existing design elements
operating model	2	10	6
target & purpose	0	0	21
process	2	10	5
setting	9	47	1
product	2	8	4
pedagogy	3	10	5
metrics	9	46	4
<u>research</u>	3	13	13
∑	**30**	**144**	**59**

3.2. New Content in the Morphology

The made changes as part of the revision are presented in this section using as a reference to the existing LF morphology [3]. In Fig. 1-8 changed design elements are highlighted in a darker green, changed characteristics in a lighter green.

#	design element	characteristics							
Design dimension 1: operating & business model									
1.1	operator	academic institution	non-academic institution	profit-oriented operator	not-for-profit organizations				
1.2	trainer	professor	researcher	student assistant	technical expert	manager	consul-tant	educa-tionalist	external trainer
1.3	development of concept	internal	external assisted	external					
1.4	initial funding	internal funds	external funds: public funds	external funds: company funds	external funds: funds from associations				
1.5	ongoing funding	internal funds	external funds: public funds	external funds: industrial funds	external funds: funds from associations	funds through product sale			
1.8	key partnerships	universities	manufacturers	consultancies	industry	incubators	service organizations	NGO	
1.9	business model for research	open models: club model	open models: course fees	closed models					

Fig. 1: Design dimension 1 "operating model".

To operate a LF sustainably an **operating and business model** is needed. For the long-term success of LFs partnerships with other universities, manufacturers, consulting firms, industry, etc. are essential, therefore a new design element has been added [6]. Besides a business model for training [3], a business model for research is needed as well.

#	design element	characteristics					
Design dimension 2: target & purpose							
2.2	secondary purpose	test/pilot environment	industrial production	innovation transfer	public image	innovation	demon-stration
2.5	targeted industry	mechanical & plant eng.	automotive	logistics	transportation	FMCG	aerospace
		chemical industry	electronics	construction	insurance / banking	textile industry	health care
		agriculture	life science	pharma	mining	new economy	…
2.6	subject-related learning contents	lean management	energy & resource efficiency	industrial engineering	global production	Industry 4.0	Industry 5.0
		product creation process	circular economy	sustainability/ social impact	business engineering	artificial intelligence	smart information logistics
		object recognition	engineering education	digital twin/ service twin/ human twin	factory planning	additive manufacturing	workers participation

Fig. 2: Design dimension 2 "target & purpose".

The three main **targets and purposes** of LFs are training, education and/or research [7]. The secondary purpose extends this aspect, e.g., with innovation and demonstration. Furthermore, new targeted industry sectors have been added, for example agriculture or pharma. In the last years, the subjects that are learned in LF have been changed, new learning contents were added for example Industry 5.0, circular economy, artificial intelligence, and additive manufacturing.

Design dimension 3: process											
#	*design element*	*characteristics*									
3.1	demonstrated product life cycle phase	product planning	product development	product design	rapid prototyping	manufacturing	assembly	logistics	service	recycling/ remanufacturing	
3.2	factory life cycle phase	investment planning	factory concept	process planning	ramp-up				maintenance	recycling/ remanufacturing	
3.4	technology life cycle phase	planning	development	virtual testing					maintenance	modernization/ modification	
3.8	manufacturing organization	fixed-site manufacturing	work bench manufacturing	workshop manufacturing	flow production	changeable manufacturing principles					
3.10	manufacturing methods	cutting	primary shaping	forming	joining	coating	change material properties	additive manufacturing			
3.12	number of factory areas	<3	3-5	6-9	10-15	15-20	>20				
3.13	intralogistics automation	manual	semi-automatic	automatic							
				without robotics	with robotics						

Fig. 3: Design dimension 3 “process”.

Processes in LFs should be authentic, multi-stage and comprise both technical and organizational aspects [3]. Regarding the importance of sustainability in production, the topic circular economy will be more relevant in the future [8]. Therefore, additional demonstrated phases in the life cycles of the product, factory and technology have been added. To address the topic resilience in production, the manufacturing organization should regard manufacturing principles of changeability [9]. Additionally, in the design phase the number of factory areas, e.g., assembly, sawing, should be discussed. Moreover, the degree of intralogistics automation should be discussed in the LF design, e.g., manual, semi-automatic or automatic processes.

Design dimension 4: setting									
#	*design element*	*characteristics*							
4.5	changeability dimensions	product	process	organization	building & layout	material flow			
4.7	number of different states	1	2-3	3-5	>5	individualized to target groups			
4.8	integrated digital technologies	data acquisition	traceability	data processing (e.g., AI)	assistance systems	digital fabrication	simulation		
		data management & visualization	automation technology	cybersecurity	network technologies				
4.9	location of the LF	own location	integrated in another factory	integrated in another building	digital location				
4.10	role of the operator	participants	human resource of the organization	trainer	salaried personnel				
4.11	meeting room	no separated room	integrated in the shop floor	separated room					
4.12	automation pyramid	sensors & actuators	PLC	SCADA	MES	ERP	SES		
4.13	ICT protocol	physical	data	network	transport	session	presentation	application	more than application
4.14	assistance systems	digital assistance	physical assistance	robots					
				industrial robots	light weight robots	wearable robots			
4.15	traceability	radio based technology	optical technology						

Fig. 4: Design dimension 4 “setting”.

The **setting** of the learning environment should be changeable and additionally to a physical factory, virtual extensions can be used optionally [3]. To address changeability in the training sessions, different states of the LF should be considered [10], for example in a LF for lean production a wasteful and a lean state can be defined. As digital technologies promise higher productivity, those should be considered in the design phase [11]. Especially for the automation pyramid, assistance systems and traceability systems, the morphology comprises different options. Furthermore, the location of the LF in relation to other buildings, the role of the operator and the integration of a meeting room should be defined in the design.

Design dimension 5: product								
#	*design element*	*characteristics*						
5.1	materiality	material (physical product)	immaterial (service)	digital (data, software)				
5.3	product origin	own development	development by participants (changing ideas)	partial development	external development			
5.7	no. of variants	1 variant	2-4 variants	5-20 variants	>20 variants	flexible, depending on participants	determined by real orders	customizable
5.8	no. of components	1 comp.	2-5 comp.	6-20 comp.	21-50 comp.	51-100 comp.	>100 comp.	customizable
5.10	weight of the product	≤ 1kg	1 kg – 10 kg	10 kg – 25 kg	≥ 25 kg			
5.11	components	physical: mechanical	physical: electric	physical: electronic	digital			

Fig. 5: Design dimension 5 "product".

The **product** of a LF is usually physical but new LF concepts also regard services (logistics or maintenance) [12], and digital products (data and software). Based on customer-individualized production, the number of variants and components can be additionally customizable. For example, if the focus of the LF is on learning lean methods, the product as a whole should be easy to understand. Additionally, if errors are to be integrated into the product to train problem-solving techniques, it is advantageous that the weight of the product is low.

The dimension previously known as "didactics" has been renamed to "**pedagogy**" in order to reflect the learner-centric approach that LF are meant to adopt. As such, this dimension is concerned with the description of activities and methods related to learning and evaluation. To address the limited mapping ability in LFs [13] didactical extensions can be used, e.g., case studies or simulations. Based on the didactical principle of autonomy [14], the learning sessions in LF should be personalized to a different degree. While in-person participation in LF is recommended, the participation capability can be more flexible with hybrid or remote concepts.

Design dimension 6: pedagogy								
#	*design element*	*characteristics*						
6.8	type of learning activities	tutorial	practical lab course	seminar	workshop	project work	flipped classroom	business scenario (e.g., product life cycle)
6.9	standardization of trainings	standardized learning modules	customized learning modules	modular learning modules				
6.11	evaluation levels	feedback of participants	competency measurement	transfer to real factory	economic impact of training	return on training		
6.12	evaluation methods	knowledge test: written test	knowledge test: oral test	written report	oral presentation	practical exam	360-degree assessment	none
6.13	learning factory extensions	case study	role play	simulation	none			
6.14	degree of personalization	participant personalization	group personalization	none				
6.15	participation capability	in-person participation	hybrid participation	remote participation				

Fig. 6: Design dimension 6 "pedagogy".

Additional **metrics** are summarized in an own design dimension. Important aspects in the design of LF have been added as new design elements, e.g., the number of integrated learning modules in education, the number of qualified people trained per year, the number of education sessions and industry trainings per year, costs for the setup and operation as well as peer-reviewed publications related to LF per year.

Design dimension 7: metrics											
#	design element	characteristics									
7.3	no. of integrated learning modules	undergraduate program					graduate program				
		1	2-4	5-10	>10	modu-larized	1	2-4	5-10	>10	modu-larized
7.4	aver. duration of a learning module	≤ 0.5 day	0,5 days – 1 days	1 day – 2 days	2 days – 5 days	2 days – 5 days	5 days – 10 days	10 days – 20 days	> 20 days		
7.5	no. of highly qualified people trained per year	< 50	50-200	201-500	501-1000	>1000					
7.6	size of LF	< 50 sqm	50 sqm - 100 sqm	100 sqm - 300 sqm	300 sqm - 500 sqm	500 sqm - 1000 sqm	> 1000 sqm				
7.8	no. of education sessions per year	< 5	5-15	15-30	30-50	>50					
7.9	no. of industry trainings per year	< 5	5-15	15-30	30-50	>50					
7.10	no. of dissemination events per year	< 5	5-15	15-30	30-50	>50					
7.10	setup costs	< 10,000 €	10,000 € - 100,000 €	100,000 € - 1 million €	> 1 million €						
7.11	operational costs per year	< 10,000 €	10,000 € - 100,000 €	100,000 € - 1 million €	> 1 million €						
7.12	peer-reviewed publications related to LF per year	< 5	5-15	15-25	> 25						
7.13	third party funds related to LF per year	< 10,000 €	10,000 € - 1 million €	1 million € - 20 million €	> 20 million €						

Fig. 7: Design dimension 7 “metrics”.

While pedagogical aspects to the main purpose of education and training are further specified as a separate design dimension, the main purpose of **research** has not been further detailed so far. Therefore, the research topics that have been part of the design dimension “target and purpose” have been added in a new design dimension. Moreover, the research object can now be specified in more detail, e.g., new technologies, new processes, new methods. Involved persons in the research topics range from top grad researchers (like full professors) to first stage researchers (like PhD students). While the LF is an enabler for the mentioned research topics, the LF itself can also be the object of research, e.g., for the design or improvement process of a LF.

Design dimension 8: research								
#	design element	characteristics						
8.1	research topics	lean management	energy & resource efficiency	industrial engineering	global production	Industry 4.0	Industry 5.0	
		product creation process	circular economy	sustainability/ social impact	business engineering	artificial intelligence	smart information logistics	
		object recognition	engineering education	digital twin/ service twin/ human twin	factory planning	additive manufacturing	workers participation	
8.2	research object	new technologies	new processes	new methods	new management tools	new materials	new didactical methods	new fundamental discoveries
8.3	involved persons in the research process	top grade researcher (e.g., full professor, director of research)	senior researcher (e.g., associate professor, senior researcher)	recognized researcher (e.g., assistant professor, post-doc)	first stage researcher (e.g., PhD student)			
8.4	research scope	LF as research object	LF as research enabler					

Fig. 8: Design dimension 8 “research”.

4. Discussion

The LF morphology extension further standardizes and details the first steps in the LF design. This is especially important for research institutions as well as companies that like to develop a new LF or improve an existing one. The results also claim a high degree of general validity given the large number of institutions involved in the process as well as the high number of LF developed by the authors. Still, the next step should involve LF stakeholders, industry consultants, and equipment providers to further evaluate the morphology. The benefit in using the morphology comes from its simple use. So, it was important to add only the necessary elements without becoming too complex. Therefore, the criteria listed above were used. The specified design elements are partly mutually dependent, which must be kept in mind when applying. As the LF concept is constantly evolving together with technological developments, further updates to the morphology are expected and necessary to maintain its relevance.

5. Conclusion

Although future extensions to the LF morphology were already mentioned in its first version, this publication represents the first fully comprehensive work in which the morphology is revised and extended. The revised version of the LF morphology supports the design of new LF, as the new design elements further detail the planned LF concept. Moreover, the revised morphology helps to classify and compare existing LF and creates a common understanding. In a next step, the whole morphology will be published via the IALF. The results of this publication serve as the basis for a guideline with which LF can be designed. This guideline will be drafted by the members of the Working Group "Learning Factory Design" of the IALF in the next step. The complete morphology will be available on the IALF homepage after the publication of this research paper [15].

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