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Learning process planning for special machinery assembly

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Abstract

Special machinery manufacturers provide customer specific solutions. These specific solutions create tremendous challenges for employees during first assembly, erection at the customer site and future service activities. Especially in serial production, Learning Factories proved to be an effective solution to convey competencies for employees on how to improve production related processes. In special machinery, product specific competencies like working principle and built up of machines are additionally important. Therefore, to utilize the advantages of Learning Factories in special machinery it is necessary to shift the focus from processes to products. This results also in additional requirements regarding versatility of the technical infrastructure. A learning process planning approach which addresses requirements of special machinery assembly, has been designed. It was exemplarily applied for the knowledge transfer regarding the assembly process of an integrally geared compressor. As every product in special machinery is unique, learning process steps have to be adapted for each product. Therefore, a shorter assembly learning process is necessary to cope with continuing product innovations and customer requirements. Around a basic compressor casing that represents the least common denominator regarding product variety, specific interchangeable sub-assemblies for product variants are implemented that utilize digital content. This allows a fast adaption to different product variants.

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1. Initial situation and motivation

Special machinery companies are producing customized one-of-a-kind products for a huge variety of niche markets. A large special machinery company, located in Berlin, Germany produces turbomachinery for gas compression. The main product of this company are integrally geared compressors with a final compression of up to 250 bars and volume flows of 550,000 m^3/h [1]. These integrally geared compressors are individually designed and built according to customer needs. They can be classified into five main categories based on their process gas type: air, carbon dioxide, fuel gas, cold gas and special process gases. Depending on the process gas, every category requires different handling and treatment of parts, different sealings, different auxiliaries and different lubricants. Each of these compressors is a one-of-a-kind product, especially designed and engineered for customer needs. Depending on the required final pressure and gas flow, the integrally geared compressors can consist of between one and ten compression stages. The size and the number of parts of each stage differ, but the arrangement of parts within each stage mainly stays the same for each compressor. These conditions lead to several challenges for Field Service Engineers (FSEs). FSEs are responsible for the

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first erection of these compressors at the customer site and for the maintenance and repair during the whole compressor life-cycle, which normally lasts for more than 25 years. Additional challenges are given by the diverse cultural and language background of the FSEs as well as their high age range from approximately 25 to 60 years. They are all highly skilled in the assembly of special machinery in general. The pre-knowledge and the skill level about integrally geared compressors and their assembly ranges from basic knowledge to experienced worker.

Until now, trainings for these FSEs consisted of a theoretical part, taught by product experts for the different compressor parts, and practical training. The practical training was performed on already assembled compressors which were almost ready to be sent to the customer. During the practical exercise, assembly errors by the FSEs could easily lead to damages on sensible parts. This was followed by immense delivery delays due to new production and procurement of the damaged parts. Therefore, for most assembly processes FSEs were only allowed to watch experienced workers perform the required steps. Previous solutions for this focused on a better visualization together with a higher degree of interaction in assembly instructions to transfer the required assembly knowledge to the FSEs [2, 3, 4, 5].

2. Learning Factories and Learnstruments

A Learning Factory is a learning environment that resembles a real factory. It encompasses authentic processes and multiple work stations to manufacture a physical product. In addition to technical aspects, organizational aspects of a factory are included as well. In a broader sense, Learning Factories can also use a virtual setting and/or provide a service instead of manufacturing a physical product [6]. The enhancement of the physical setting with additional virtual components can be useful to overcome physical limitations, e. g. in regard to technically challenging components or to demonstrate long-term effects [7, 8].

A major benefit of Learning Factories is the similarity between the learning and working environment of the learners. Especially for employees, this is an opportunity for additional motivation and it facilitates the transfer of the newly acquired skills to their own work place [9]. Learners have the opportunity to practice the learning content in a realistic but also safe environment. They can test different scenarios and make mistakes to learn from, without negatively interfering with the real value creation process [10].

A detailed approach for the competency driven design of Learning Factories on three levels was proposed by Tisch et al. (see Fig. 1). On the macro level, learning targets are defined as intended competencies and a rough infrastructure of the Learning Factory is devised. Based on specific organizational requirements and the results from the macro level, teaching modules are developed on the meso level. Finally, specific teaching-learning situations are designed in detail on the micro level. On each of these levels, two didactic transformations take place. During the first didactic transformation the relevant content is selected and learning targets are defined. Subsequently, suitable learning systems, modules and situations are developed in the second didactic transformation [11].

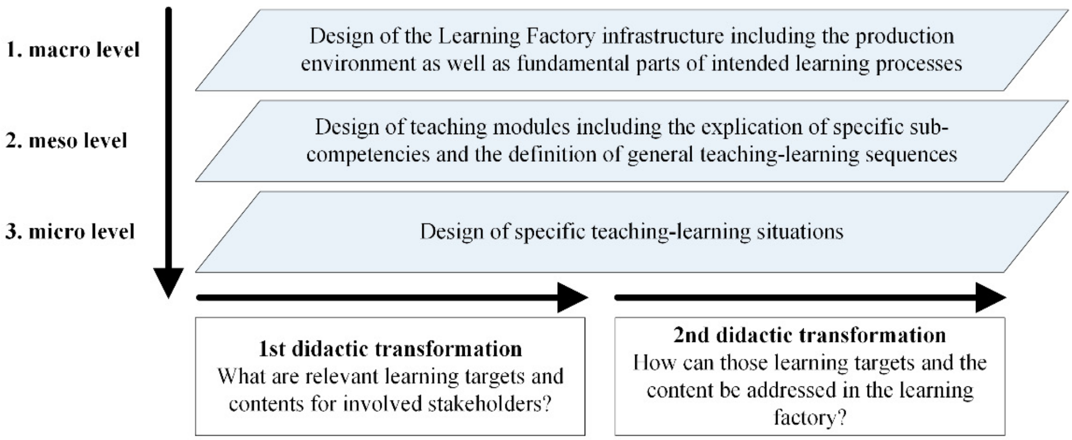

Fig. 1. Learning Factory design levels [11].

Learnstruments are another opportunity to learn in a work related environment. They “are artefacts and systems which automatically mediate their functioning to their user” [12]. Skills and knowledge can be transferred together by a combination of learning and working environment [12]. Teaching and learning productivity increase, encouraged by the simple use of Learnstruments. They foster a social sustainability development in an organization by increasing employees’ knowledge and skills. Different scenarios describe how Learnstruments help to improve manual assembly process efficiency [3, 4, 5, 13].

3. Gap

Learning Factories are mainly established and used for training in the context of serial and mass production. They focus on teaching process knowledge and methods on how to improve existing processes, e. g. through Lean Management, reconfigurability in factory planning, Industry 4.0 and energy and resource efficiency [14]. The assembly of parts and the product itself are normally not the training focus. They are only used as examples on which the process improvement is based on. Versatility of Learning Factories is mostly represented by the ability of equipment to adapt to two or three different products or by several assembly stations that can be arranged in a different sequence or layout [15, 16] and not by being able to teach different product variants, their assembly process and problem solving strategies for product failures.

Contrary to Learning Factories for mass and serial production, the focus for special machinery lies on the product and not on the process. In existing Learning Factories, the product only gives an example on which several strategies and processes can be demonstrated. It is frequently adapted for didactic purposes and has only minor similarities to the product the real factory produces [15] and can be exchanged easily without losing teaching content. In special machinery the closeness to the product is narrower. Table 1 gives an overview about the main differences between the segments and their influence on Learning Factories.

Table 1. Comparison between special machinery and serial production

Criterion	Special machinery production	Serial production
Units produced per year	low	high
Number of product variants	high or infinite	low or medium
Product type, availability	on customers specification, on demand	standard variations, stocked
Product price	high	low or medium
Company size	small or medium	medium or big
Customer location	global	global
Flexibility of production	high	low
Process	individual and slightly standardized	strongly repetitive and standardized
Degree of automation	weak linkage of plants, equipment and material flow	medium or strong linkage of plants, equipment and material flow
	Effect on Learning Factories	
Learning Factory mutability	an unlimited number of product variants and minimum standard processes require a high versatility	a limited number of products and lots of standard processes require a slight or medium versatility
Essential for design	product	process and material flow

To date there is no concept on how the many advantages of a Learning Factory can be utilized in the special machinery segment. The requirements for such a Learning Factory have not been addressed in actual literature. A procedure on how a Learning Factory can be developed for special machinery environment does not exist.

4. Concept and method

As there are many different compressor types and applications, the product knowledge becomes complex and difficult to transfer. All compressor variants should be available for training, which is impossible, as the teaching concept needs to focus on an affordable solution. Contrary to serial production, the training concept does not need to be developed for one product with two or three variants and a yearly production of 10,000 or more than 100,000 units, but for a near infinite number of variants and 50-70 high-priced units per year. Therefore, the training cost per unit is comparably higher in one-of-a-kind production [17].

The curriculum design, developed by Tisch et al. [11], has been used as a basis for the development of a special machinery Learning Factory. Nevertheless, several changes have been implemented to suit the needs of this production segment. Fig. 2 gives an overview about which steps of the original curriculum design method have been used, indicated by small representations of the original method at the top. The introduced compressors vary in more than 30 different main parameters. Because of confidential reasons, only the assembly of a so called “dry gas seal” is explained exemplarily in the following representations.

Meso and micro level only differ slightly from each other in the original curriculum design. The first didactic transformation in the micro level is not discussed by Tisch et al. and could be the same as in the meso level. For the second didactic transformation it was necessary in the original curriculum design to select a teaching module first and afterwards single learning stations. While applying this design method in a special machinery environment a discussion about single learning stations always took place already while designing the teaching modules. Both steps are heavily interlinked and should be developed together, especially if a high degree of versatility is required. Therefore, the meso and micro level have been combined into one new base layer. This can help to increase the development speed to support the short cyclic product developments.

During the creation of specific teaching learning situations, it became obvious that iterative alternation between meso and micro level as well as first and second didactic transformation happened on a frequent basis. Therefore, the proposed new curriculum design model is based on a circular draft as can be seen in Fig. 3. The base design layer, is mostly comparable to the macro level of the original design. Production type, purpose and target group are defined here at first, before describing the learning goals.

Then the learning modules are defined in the second didactic transformation. After the basic infrastructure is designed in the base design layer, it is only necessary to re-discuss it, when new learning goals or modules have to be included into the Learning Factory. This might be the case for the sealing example, when a new sealing type has been developed. The meso and micro level are combined to a new detail design layer. In this layer, the competency and workflow transformation are used in an alternating way until a final concept is developed.

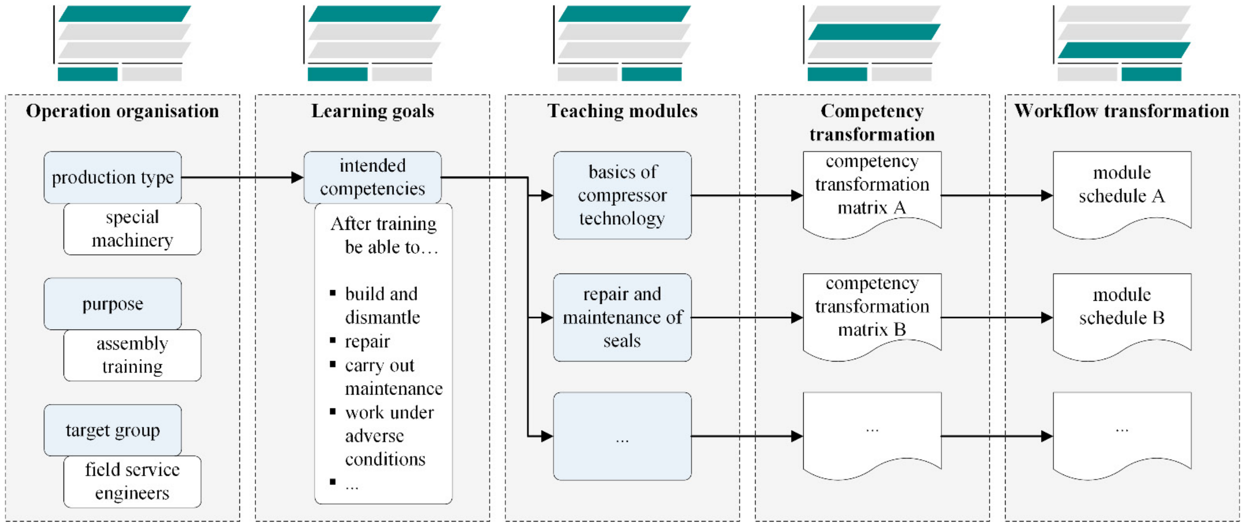

Fig. 2. Overview about steps used for the new design model based on [10].

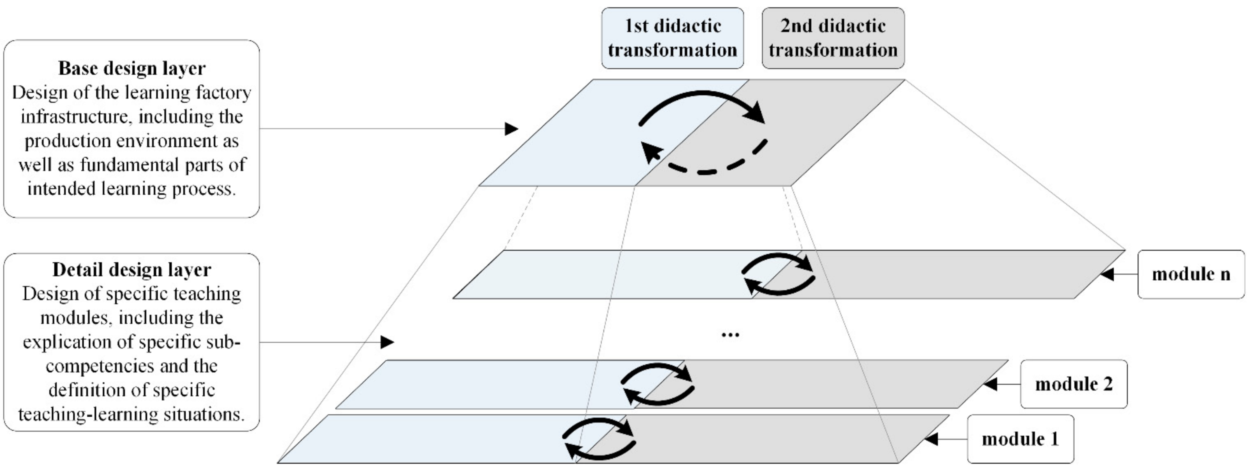

Fig. 3. Proposed new curriculum design model for special machinery learning factories based on [10].

The main differences between the both curriculum design models can be summarized as follows:

- Alternating flexibly between original levels became important because some levels affected each other. Therefore, the new design has a higher degree of flexibility.
- For the second didactic transformation, simultaneous work on meso and micro level was necessary to create the module workflow plan based on the competency transformation. This includes learning processes, teaching methods and the teaching-learning situations; e. g. the choice of the appropriate teaching method was easier when it was taken in the context of the teaching-learning situation.
- Meso and micro level are combined into a new detail design layer.

4.1. Base design layer

In the first didactic transformation, requirements analysis and definition as well as operationalization of learning targets take place. In detail, the organizational environment is determined by the special machinery industry, the organizational target is the assembly training and the target group are FSEs. Based on these, intended competencies are derived. For confidentiality reasons only one competency will be named here exemplary: assembly and disassembly of an integrally geared compressor. In the second didactic transformation, the configuration and design of technical and didactical infrastructure takes place.

4.2. Detail design layer

In the first didactic transformation teaching modules are designed and then the intended competencies are transformed into corresponding actions as well as professional and conceptual knowledge as visualized exemplarily in Table 2. In the second didactic transformation a workflow transformation takes place. Here another advantage of the compressed design model becomes visible. The choice of the appropriate teaching method was easier, when it was taken in the context of the specific teaching-learning situation. The original concept was designed to choose the appropriate teaching method without knowing how the teaching-learning situation would look like.

Table 2. Competency transformation for the intended competency "dry gas seal assembly", adapted from [10]

no.	intended sub-competency	corresponding action (performance)	professional knowledge (what), conceptual knowledge (how, when)
2.1	ability to detect which parts of a dry gas seal are not working or are responsible for a malfunction	check and evaluate the dry gas seal and its parts and decide if something has to be exchanged (preventive maintenance)	knowledge about normal conditions and appearance of a dry gas seal
		find possible problems or failures based on the condition of the dry gas seal (error and cause detection)	knowledge about problems/errors, which could affect the function of the dry gas seal
…	…	…	…
2.13	ability to assemble a dry gas seal	explain the necessary steps for the assembly of a dry gas seal	knowledge about necessary sequence and possible difficulties for assembly of a dry gas seal
		execute the necessary steps in the right sequence for the assembly of a dry gas seal	knowledge about the necessary assembly steps and their sequence as well as required tools, measurement devices and equipment

4.3. Final design

To enable an efficient knowledge transfer process, the product variants have been broken down as far as possible to one simplified compressor, consisting of the most used components and therefore representing the least common denominator. The relevant components were selected according to the frequency of necessary (dis-)assemblies of the different compressor types, during production and performed maintenance activities. The simplified compressor can be used to teach basic knowledge about components and train basic assembly principles. For parts that are only used for few special compressor variants, separated versatile Learnstruments are created. These can be exchanged or updated according to the specific need of the learners. By this, the training for special compressors becomes individually adaptable for the learner and the learning content. Fig. 4 gives an exemplary outlook on how the technical design of the new learning environment will look like.

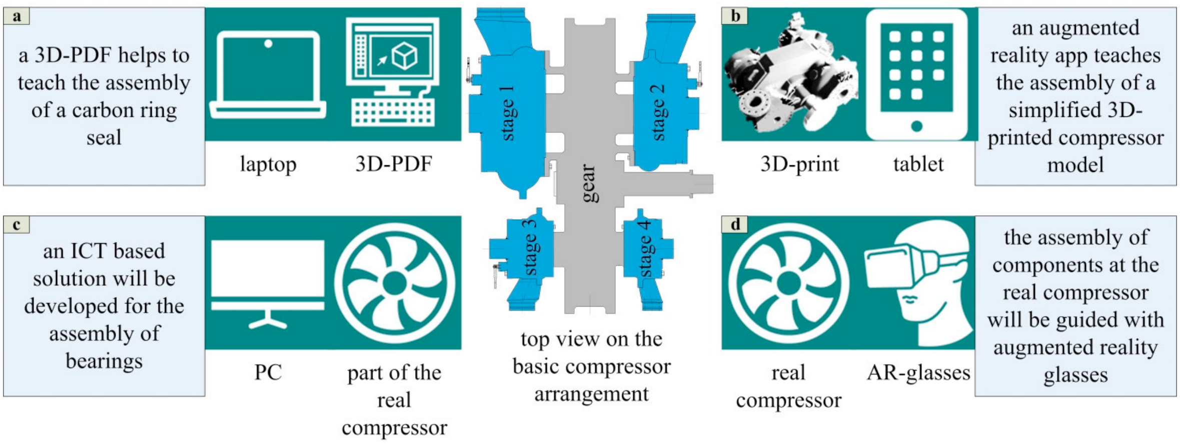

Fig. 4. Technical design and conceptual layout for the new versatile learning environment.

Four exemplary Learnstruments are arranged around the basic compressor in the middle. Learnstruments (a) and (b) have been already fully developed and implemented and (c) and (d) are still under development. The 3D-PDF (a) was tested with a group of international students and Field Service Engineers and compared to alternative image based instructions. By using the 3D-PDF the assembly time during learning was reduces on average by 15% compared to utility films and 18% compared to illustrated instruction [4]. Additional Learnstruments will be developed in the future to address the assembly of all compressor parts. All of them use a versatile approach where:

- the physical Learnstruments part is divided into a general section of the compressor with a standardized connector, allowing to use and implement an endless number of different product variants and
- Information and Communication Technology (ICT), which allows a fast adaptation to different product variants by interchangeable digital context.

5. Summary and outlook

An existing concept for the development of Learning Factories has been adapted for the requirements of special machinery and exemplarily implemented at a turbomachinery manufacturer. The existing curriculum design model has been condensed and shortened to be able to implement new teaching content faster in the future. A higher flexibility between the different new layers was used to be able to react to affections between layers. A condensed working method on the new detail design layer helped to create the module workflow plan, based on the previous competency transformation, which now includes learning process, teaching methods and the teaching learning situations. The results are a prearrangement and post-processing list for several training modules as well as detailed workflow description lists for these modules.

The proposed design allows learners to achieve basic knowledge about the compressor and its assembly by using an augmented reality app together with a simplified 3D-printed compressor model, see Fig. 4 (b). In a next step, they can learn the full assembly of one compressor variant at a real compressor by using several 3D-PDFs, see Fig. 4 (a). And finally, aided by several Learnstruments around the compressor, learners are enabled to understand the differences in assembling specific product variants. By now the basic compressor casing, that represents the least common denominator regarding product variety, is installed at the special machinery manufacturer. First specific interchangeable sub-assemblies for product variants are already developed and are being implemented. The future learning environment will consist mainly out of versatile Learnstruments using a high level of ICT.

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