Developing a learning factory to increase resource efficiency in composite manufacturing processes

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Abstract

Learning factories serve as platforms to ensure research findings are disseminated into industrial practice. A critical success factor for an effective technology transfer via a platform is the definition of a representative process chain. Due to the increasing demand for lightweight components in automotive industry, established materials like steel are partially substituted by composites materials. Hence the Green Factory Bavaria was established as learning factory to demonstrate energy efficient manufacturing processes for composites. This paper contains the process and workpiece definition necessary to ensure a wide transferability of research results into various industries. Using the developed methodologies of flexible measurement concepts and machine upgrading, suitable efficiency measures are integrated in a learning concept. The obtained energy savings are discussed for selected process steps like cutting, cleaning and assembly technologies.

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1. Introduction

1.1. Definition of a learning factor’s scope

Due to nuclear phase out, German industry faces rising energy costs as one of the major challenges for manufacturing companies. Hence increasing the energy efficiency of existing machinery in manufacturing is a mid-term goal to be implemented [1, 2, 3]. In order to explore energy efficiency potentials there is a need to transfer methodologies to identify saving potentials to industry decision makers. Therefore technological best practice solutions need to be demonstrated in the environment of a learning factory.

To ensure a wide transferability of the content demonstrated and taught, an initial analysis of existing learning factories is crucial. A survey needs to be conducted in order to comply with the demand of the targeted audience. Based on these findings the specifications for a process chain to be implemented in the learning factory can be derived.

1.2. Inventory of existing learning factories in Germany

Analyzing existing learning factories in Germany operated by research institutes and private institutions like consultancies reveals that the majority of entities is located in the southern part of Germany, where the density of industrial activities is high (ref. Fig. 1). Regarding the teaching contents of those learning factories, most of them cover topics concerning industrial engineering or lean management [4, 5, 6, 7].

According to the research goal initially stated, energy efficiency has been rarely addressed by a handful of universities like Munich, Chemnitz and Braunschweig. In the associated learning factories mainly metal cutting operations with machine tools or cross-sectional technologies like pneumatics are demonstrated [8]. Yet, none of the existing learning factories addresses the specific challenges linked to the manufacturing of carbon fiber based lightweight products. Fig. 2 illustrates the trend in the demand for carbon fiber,
showing a tripling of the global production output. Together with the unbroken trend towards lightweight component usage in aerospace and automotive industry and the progressing substitution of established source materials like steel the need for a new learning factory environment is apparent. [9, 10] Bayreuth therefore dedicates its learning factory to aspects of energy and material efficiency in lightweight production.

2. Conception of learning factory framework

2.1. Selection of representative manufacturing process

To define a representative process chain, expert interviews have been conducted. Based on the results the following selection criteria have been considered in order to reach industry practitioners:

- Selection of a rather new process chain with a rising dissemination and substantial ecological impact in the near future
- Implementation of a multiple-stage manufacturing process including various machines containing thermal and electrical energy use
- Integration of various materials such as metal, plastics, textiles to ensure a wide transferability to various industries

Fig. 1. Learning factories in Germany

2.2. Identification of a reference workpiece

A composite manufacturing process is requires a product that represents a wide range of possibilities and challenges associated with their fabrication. Therefore different preselected reference workpieces have been compared in respect to their usability in a learning factory. A point rating was chosen, in which three points signify a complete fulfillment of the raised criteria. One point intents an insufficient fulfillment of the criteria [12]. Besides the criteria have been emphasized through variable weighting according to their relevance for supporting an effective learning process.

Table 1. Criteria based selection of workpieces

| Criteria                  | Weighting |
|---------------------------|-----------|
| Illustration of various, composite specific manufacturing technologies | 30%       |
| Production possible in the scope of training | 25%       |
| Magnanimity character     | 15%       |
| Cost-effective production | 10%       |
| TOTAL                     | 100%      |

| Preselected reference workpiece | Hand launch glider | Smartphone shell | Frisbee | Boomerang | Filler cap |
|---------------------------------|--------------------|------------------|---------|-----------|-----------|
| Weighting                       | 3                  | 2                | 3       | 1         | 1         |
| Criteria                        | 2                  | 3                | 2       | 2         | 3         |
| TOTAL                           | 2,55               | 2,25             | 1,90    | 1,90      | 1,60      |

The hand launch glider was selected mainly because of its challenging composite manufacturing process, including the composition of sandwich structures, the lay-up automation of preimpregnated (prepreg) plys and the curing in out-of-autoclav (OOA) processes. Consequently the learning factory addresses the challenge of becoming both a place for knowledge transfer and for research activities in the field of composite manufacturing.

In the following section an overview of the realized composites manufacturing process is given.

2.3. The reference process chain

The process chain of the learning factory comprises various aspects of resource efficiency (ref. Fig. 3). It consists of seven individual steps covering all stages in the manufacturing of composite products and includes the use of production resources, in particular molding tools. Therefore the directly related production steps, such as ply placement and curing, are encircled by the steps necessary to produce, handle and clean molding tools. Besides the confectioning of the semi-finished product used in the manufacturing of composite parts, namely
the prepreg fiber material, is realized through the presence of an automatic knife cutting system (cutter).

3. Development of the learning concept

3.1. Learning concept

A main goal of a learning factory on energy efficiency is to make participants aware of energy waste in manufacturing. Besides it aims on integrating training participants into the process of identifying and quantifying energy saving potentials.

That is why a blended learning concept, based on Dale’s cone of experience was selected in order to ensure an efficient know how transfer [13]. The diagram in Fig. 4 shows Wiman and Meierhenry’s adaption of Dale’s cone of experience [14].

![Dale's cone of experience](image)

Participants generally remember:
- Participants are able to:
  - 10% of what they read: Define, Describe
  - 20% of what they hear: List, Explain
  - 30% of what they see: Watch, Demonstrate
  - 50% of what they hear and see: Apply, Practice
  - 70% of what they say and write: Analyse, Design
  - 90% of what they do: Simulate or model a real experience, Create

As illustrated, know how transfer requires a high amount of practical hands-on experience to foster and expand the knowledge acquired in theoretical lessons.

The targeted learning content of energy efficiency includes a wide and interdisciplinary field of work. Hence the structure of the seminars involves formats like group work, hands-on workshops (e.g. detection of pneumatic leakage of machines) and demonstrations (e.g. allocation of flexible measuring concepts).

3.2. Integration of participants: Method based identification of saving potentials

In order to achieve the goals stated in 3.1 and improve the dynamic interaction between the participants in the learning factory environment, a new game-based learning method was developed, called energy-bingo.

The basic structure of this method is derived from the plan-do-check-act (PDCA) cycle; an iterative management method used to control business processes for continuous improvement [15, 16, 17]. The adaption of this method is presented and illustrated in Fig. 5.

![Energy-bingo](image)

In the experience phase participants get to know a specific process step (e.g. ply cutting, mold production, etc.) either through a detailed explanation from a training supervisor or by the interaction with the process through hands-on experience. Hands-on experience involve challenges like the identification of electric loads in a machine tool that need to be completed successfully in a certain time. Training participants are than asked to estimate resource consumption (e.g. power, heat, etc.) in the process and present their educated guess on a predesigned process specific graph or other template. In the following step resource consumption is precisely quantified using flexible measurement concepts adopted from preceding research work [18, 19]. Based on the measurement results the participants get an immediate feedback on their estimations and as a result are encouraged to have reflective discussions with the training supervisors and other participants. Besides the experience helps to consolidate theoretical knowledge and improves the participants competence to assess and quantify saving potentials. The enhanced awareness on aspects of resource efficiency generated through the use of the presented
game-based learning method is supposed to motivate participants to transfer the acquired knowledge to their sphere of influence in a company. Corresponding to the acting step (A) in the PDCA cycle, the last step of the presented methodology is therefore denominated the name “transfer”.

Estimate Measure Transfer Experience

Fig. 5. Steps of integrating participants through game-based learning

In the following section the presented methodology is discussed by giving two examples.

4. Selected use cases

4.1. Cutting process

In this example training participants had to investigate the energy consumption of a cutter. The learning objective in this specific process step was to identify the main consumers of electric power among all machine components (1 - 6 Fig. 6).

Applying the above described method, the training supervisor first demonstrated a typical cutting process used in composite manufacturing and explained the functionality of the different machine components involved.

The electrical components in a cutter include: a vacuum pump (1), a cabinet fan (2), a conveyer motor (3), three servo motors to move the cutting knife in x-, y-, z-direction (4), knife motor (5) and a machine control unit (6).

After experiencing the process live and identifying the different machine components, energy-bingo was conducted. For that reason the training participants had to be evaluated the expected electric power consumption per component. As illustrated in Fig. 7 they were asked to mark their educated guess in a predesigned diagram using stickers or adhesive tags.

This was followed by the live installation of a measurement system suitable to assess electric power consumption of machine components (7 Fig. 6), thus promoting the knowledge transfer on measurement concepts from preceding theoretical lessons.

Subsequently the measurement data was visualized and the participants received a feedback on their educated guess during energy-bingo.

Comparing estimates and real consumption date the measurement reveals that most of the participants evaluate the servo and conveyer motors as biggest single consumers. However the vacuum pump, which is necessary to fix the

Fig. 6. Analysed cutter and its components

Fig. 7. Energy-bingo as an instrument to integrate participants in the measurement-based machine examination process
material during cutting, consumes the most energy with a share of 95 percent. Concerning the participants guesses on absolute values and the measurement data, no correlation could be detected.

![Fig. 8. Energy assessment of the prepreg cutting process [21]](image)

As a feedback stated by the participants during the Green Factory training, the example of the cutter was found to represent a practical use case. It indicates that the expected experience based energy assessment -even by experts- often fails. This demonstrates the benefit of the use of multichannel measuring concepts. Furthermore energy bingo serves as an instrument for integrating participants and shaping the participants’ ability to access the component specific energy consumption of machinery. Already while setting their guess they start discussion among each other how to assess and optimize the energy consumption of the machine. In this case the main approaches for a green machine upgrading are the reengineering of drives and the routing of the air flow with saving potentials of 24 percent.

4.2. Machining process

Another example for the application of game-based learning and in particular energy-bingo was the demonstration of a milling process.

The curing of composite parts requires molds; therefore the influence of different raw materials on the energy consumption in their production was presented to the participants. The mold model to produce the reference workpiece selected in 2.2 is illustrated in Fig. 9. The milling center used to perform the test had a drive power of 13kW at the working spindle. The raw materials used were an aluminum block (AlZnMgCu1,5) and a polyurethane (PUR) based working board material.

![Fig. 9. Reference mold model](image)

The learning objective in this example was to discuss possibilities and quantify energy savings in the manufacturing of molds through a substitution of aluminum with polyurethane. Besides they had to give an educated guess quantifying the expected energy saving potentials.

The participants discovered several possibilities to reduce energy consumption in the machining of mold materials. For instance, they recognized that decreasing cutting speed, axial and line feed can reduce cutting forces and subsequently average power consumption during machining. Besides they acknowledged that focusing on the reduction of machining time might be an even more advisable strategy since standby power consumption and auxiliary components (e.g. lubricant pump, compressed air etc.) are responsible for a major share in total power consumption of machine tools [20]. Furthermore, the participants discussed the possibility for dry processing in case of the polyurethane board material. As an effect, the lubricant pump could be disabled reducing the total power consumption of the milling center.

In order to quantify the possible savings, further information was given to the participants. This included material parameters such as density and hardness, the dimensions of the block and the machining parameters for roughing and finishing operations.

![Fig. 10. Power consumption in mold production](image)

The measurement date revealed that the machining time for the reference mold model was 8 percent higher in case of the aluminum block material. Considering average power consumption, it was 7 percent lower in the processing of a PUR working board material even though the axial and line feed were higher. As a result overall saving potential of 15
percent were realized by changing the raw materials in the mold production.

Comparing the energy saving potentials revealed from measurement date and the estimates given by the participants during energy-bingo, participants estimated saving potentials to be between 2.5 – 15 percent higher.

In comparison to the first use case the discussion generated by the help of energy-bingo was comparably vivid. The ideas for optimization generated showed that most participants are familiar with the cause and effect of measures to realize energy savings. However a lack in the ability to quantify these potentials became apparent.

5. Conclusion and Outlook

The developed learning factory represents a platform to transfer relevant know-how considering the improvement of energy efficiency in industry. It includes various manufacturing technologies and materials and therefore offers a wide transferability. Besides carbon fiber specific aspects have been addressed in the design of the manufacturing process and the selection of the reference workpiece, thus guaranteeing relevance for industry and research.

Considering the game-based learning method, the discussion between the participants stimulated through the hands-on interaction with the process and the measurement date was found to be the main achievement of its implementation. Observation and feedback showed that the game-based learning approach helped participants to establish a better understanding of the process and its related measurement results. Game-based learning is therefore evaluated an effective tool to improve the capacity of responsible people in the field of resource efficiency to assess and quantify saving potentials correctly.

With the integration of interactive elements like energy-bingo the transferability of the taught learning content is ensured. Applying the learning concept in the conducted training was successfully evaluated regarding the requirements formulated by the participants.

At present state the main focus of the learning factory (Green Factory Bayreuth) is the transfer of saving potential considering electrically operated manufacturing processes with main focus on drives and control technologies.

In a next step the process chain for composites manufacturing will be completed by adding the curing process. This process step covers heating technologies and thermal energy consumptions. Hence the subject-matter of the training will be extended by integrating further aspects like heat recovery and insulation. Concerning the game-based learning approach presented in this study, a detailed examination of its impact on the participants’ learning success will be conducted.

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