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Designing learning environments for energy efficiency through model scale production processes

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Abstract

In the recent past global industries started to take action towards energy efficient manufacturing to oppose the challenges of the increasing demand for natural resources. Substantiated competencies on energy efficiency measures can serve as a competitive advantage especially in energy intensive manufacturing environments. Learning environments that build upon action based learning have proven to be an effective instrument for developing competence in manufacturing. Evolving from environments that focus on traditional command variables related to cost, quality and time, learning environments especially designed for energy efficiency are the subsequent step.
To enable the competence development on energy efficiency in academic and occupational education a design approach for learning environments is presented. The initial focus is set on the machine level. The model scale is chosen due to good accessibility, less space and investment requirements compared to industrial scale learning environments. A main consideration for the design is the reproduction of the surrounding machine periphery entailing a significant energy demand. Additionally, potential efficiency measures need to be aligned of the requirements on the model scale. The case of a CNC milling center is presented and evaluated concerning technical functionality of the designed milling center.

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Keywords: energy efficiency; machine level; model scale, learning environment

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1. Introduction

Instruments for action based learning have become established both in occupational qualification and academic education [1][2][3]. Learners are enabled to internalize knowledge and practical skills through self-determined actions. In manufacturing education learning environments are typically designed as learning factories. These environments are specifically designed to allow the understanding of phenomena from industrial applications and foster the learning of adequate action strategies towards these phenomena [4][5]. Current learning environments offer a broad range from industry to model scale approaches with respective advantages and challenges.

Energy and resource efficiency has become a topic of interest in various manufacturing industries. In the last years a broad range of methods and tools towards energy and resource efficient factory environments has been developed and applied in industry. As a consequence the development of knowledge and skills in these fields becomes more relevant in academic education and occupational qualification. To foster the competence development on energy efficiency in manufacturing, an approach for a model scale learning system is presented.

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2. State of the art

A key result from examining manufacturing environments from an energy perspective is the dynamic character of energy demand. On the machine level this behavior depends on the specific actual state of the machine [6][7][8]. The machine state is determined by different shares of energy being typically distinguished between base load and specific process load. The base load covers the energy demand to ensure a functional mode of operation whereas the process load covers the productive machine operation [6][7]. While in manufacturing processes the process load is often dominated by one main functional module, e.g. the tool spindle, the base load encompasses the machine control as well as machine periphery, e.g. cooling or exhaust systems [9]. Energy load profiles are derived from appropriate measurements to analyze the energy demand for different levels of manufacturing systems [6]. On the machine level the energy demand is metered during machine setup and relevant operation modes to identify the share of single or all machine elements [9]. With this information it becomes possible to distinguish between non-productive and productive energy demands [10]. Energy efficiency in manufacturing refers to the amount of resources required to produce a given level of output with the superordinate goal to minimize the amount of resources to achieve a given output level [11]. To address the topic of energy efficiency in manufacturing a variety of organizational and technical measures have been developed and implemented in industry [12]. Besides electrical energy, manufacturing processes use further forms of energy, e.g. compressed air. All energy forms need to be taken into account for an integrated view that allows the identification of main drivers for ecological and economic impacts.

Current learning environments in manufacturing can be classified as industrial and model scale approaches (see Table 1). Industrial scale learning environments are often set up as so called learning factories that recreate a real factory environment, e.g. [5]. This approach typically allows an accurate depiction of industrial phenomena but requires substantial efforts for setup and operation, e.g. industrial machine tools or own buildings. In contrast, model scale environments are often limited to few phenomena or processes rather than showing elaborate interactions within the observed systems.

Table 1: Characteristics of industrial and model scale learning environments.

	Industrial scale	Model scale
Benefits	– Realistic depiction of industrial phenomena – Good transferability of industrial methods and tools	– Good approachability – Lower financial and personal resources for setup and operation – Lower space requirements and investment
Disadvantages	– High efforts for implementation – Occupational safety	– Functional modules with limited scope – Abstraction to industrial problems

The success of learning environments in manufacturing is related to the conveyed competencies [2][5]. Tisch et al. identified the aligned development of educational contents and the technological infrastructure as success factors for competence development. A structured design approach is seen as crucial towards enabling this integrated development paradigm [5].

For model scale environments this implies a further challenge. The technological infrastructure needs to allow substantiated competency development, especially through recognizable effects. At the same time the limited extent requires focusing on few functional components. Current examples for model environments can be found in the fields of machining, mechatronics, robotics or assembly. Currently, there are no approaches focusing on energy efficiency.

One supplier for model scale manufacturing environments is Festo Didactic GmbH & Co. KG. The offered model scale production systems aim at different topics in engineering education and occupational qualification, e.g. mechatronics or pneumatics handling. The Festo Didactic Modular Production System (MPS) names a product line of interchangeable stations using industrial control systems and are usually limited to a base plate of 350x700 mm. Currently available MPS stations have been metered in regard to their suitability for the proposed learning environment. Two main effects could be shown (see Figure 5):

- The energy demand of the control systems exceeds the process loads for all of the tested stations (share of control systems up to 90%) as no true processing is executed, e.g. through spindles that are limited to air cuts.
- Demands from machine periphery cannot be represented adequately. The current designs focus on the respective manufacturing processes. Peripheral components from the industrial scale are not implemented as they are not required for the current learning targets.

3. Approach

The proposed approach encompasses the design of model scale learning environments to impart industry-relevant competencies on energy efficiency on the machine and process chain level (see Figure 1). The goal is to benefit from the model scale through a system that can easily be implemented into different education facilities but at the same time covers the behavior and interdependencies observed in industrial systems.

Although being designed as a generic approach for model scale manufacturing environments the initial focus will lie on three groups of manufacturing processes that have been selected from industrial application:

- machining processes
- handling processes
- thermal processes

It is intended to reproduce relevant effects regarding energy efficiency beginning with the production processes itself but as well including relevant machine periphery. Following research activities are planned to broaden the perspective by taking a process chain perspective and addressing the field of resource efficiency. A structured design process is introduced to address the challenges related to the scaling of effects and measures.

The learning infrastructure is set up within the MPS series of Festo Didactic aiming to be fully compatible with the currently existing stations that aim at other educational objectives.

3.1. Continuous improvement process, methods and tools

The learning environment follows an established continuous improvement approach in industrial applications [13]. Learners in occupational and academic contexts need to internalize a superordinate methodology being valid for different contexts of energy efficiency. Using a state of the art framework as foundation for both educational contents and technological development ensures a strong connection of both elements in competence development.

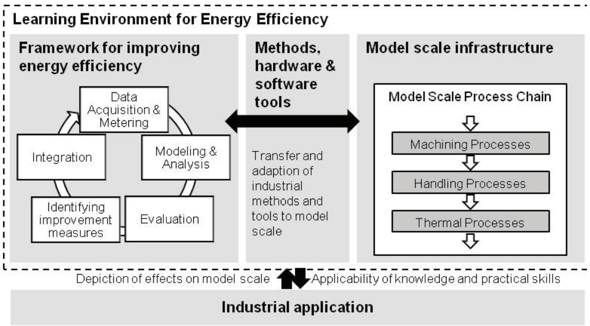

Figure 1: Approach for designing model scale learning environments for energy efficiency.

To realize the intended continuous improvement process the learning environment needs to be designed accordingly. Therefore, a number of hardware requirements as well as methods and software tools need to be provided. An overview of all identified requirements is listed in Table 2.

Table 2: Requirements of model scale learning environments for energy efficiency.

Step	Characteristics of the learning environment
Data Acquisition & Metering	Installation of metering equipment for all energy demands, setup of infrastructure to export, store and display data
Analysis	Preparation of visualization tools for the acquired data, predefined screens as well as self-determined editing
Evaluation	Provision of teaching material for selecting and interpreting KPIs, software tools for calculation
Identification of improvement measures	Methods supporting the retrieval of measures
Integration	Provision of improvement measures covering different areas of energy efficiency

3.2. Design process for model scale manufacturing processes and process chains

Electrical and pneumatic load profiles build the basis for designing the model scale processes and process chains (see Figure 2). The intended competence development requires an according technological implementation. Within the physical infrastructure the behavior of industrial processes including peripheral components needs to be recreated. To increase the approachability for learners, the model system should show a reduced functional complexity in comparison to its real counterpart. For this purpose peripheral units which would create redundant educational content will not be regarded. In the design process challenges that can arise in the downscaling of industrial components are addressed. The correspondence of both, the model scale and industrial standards, in respect to relative timing and relative load serves as evaluation criterion for the executed design.

The data collection for energy demands is executed through metering. In addition to the creation of load profiles metered data builds the basis for further visualization tools. These are required for an extensive analysis of the regarded processes. Metering strategies are required to limit the efforts for the collection of data. An industrial standard for gaining a sufficient data quality on adequate efforts is the metering of the electrical and - if applicable - pneumatic energy demand of a machine tool in different states. Typical states to be considered are the start-up routine as well as the actual processing [14]. This data allows the allocation of energy demands and operating states to events in the load profile. With the chosen metering approach the peripherals of a machine tool can generally be investigated without the effort of metering every energy demanding unit. If additional information about the process is available, e.g. technical data sheets, these can be taken into account at this point.

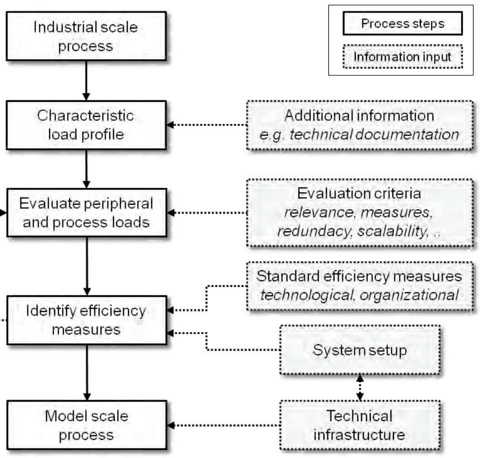

Figure 2: Design process for model scale manufacturing processes and process chains for energy efficiency.

Based on the characteristic industrial scale load profile the identified energy demanding components are investigated in regard to the following criteria:

- relevance,
- potential efficiency measures,
- redundancy and
- scalability.

Components with a very low impact on the load profile or with no improvement potential for the respective energy demand are eliminated for transition into the model scale. Also energy demanding components that show a similar behaviour to other components are neglected. Components and systems which are too complex to transform to the model scale or which will lose their characteristic behaviour in transition are intended to be substituted by other systems.

In the next step energy efficiency measures for the model scale process are identified. This can be achieved by evaluating the previously selected single energy demanding components for sensible efficiency measures. Common efficiency measures on the industrial scale can be taken into account at this point. If certain efficiency measures cannot be displayed by the chosen components for the model scale a loop back to the previous step is undertaken to restate one or more of the eliminated components. It might be necessary at this point to simulate certain effects that vanish due to the transition into a model scale with suitable components. Additional efficiency measures may emerge for a process chain set-up. The interaction of the chosen peripheral components and the actual machining component and the respective efficiency measures lead to design restrictions. Further restrictions may result from the surrounding physical and IT-infrastructure and the integration into a process chain. The presented design process remains unchanged for process chain set-ups but needs to be executed parallel to the process design to ensure the alignment of sizes and energy demands of the single processes and the interaction of the process controls as well as handling components.

3.3. User interactions related to energy efficiency measures for model scale processes

Practical interactions for implementing efficiency measures on the model scale should be based on the same approaches as on industrial scale to provide direct recognition and transferability. A short overview of organizational and technical interactions regarding energy efficiency on machine level is shown in Table 3. As indicated, not all interactions and resulting efficiency measures can be transferred physically and with full functionality to the model scale processes. To select applicable interactions on the model scale several points should be considered.

Due to different and smaller proportions of the load profile related to the components between the industrial and the model scale process interactions applied on the model scale process must have a significant impact in displacement of the load profile. Any proposed modification to the model scale process within the learning environment should be applied directly. The result in change of energy demand and efficiency should occur instantaneously so that the applied action and the reaction are clearly linked for the learner. Interactions should be easy and quick to implement.

Table 3: Selected user interactions towards the efficient use of energy in industrial scale processes [12][15]

Organisational Interactions	Technical Interactions
Improving operation modes (e.g. reduce stand-by time of peripheral units)	Appropriate dimensioning (e.g. hydraulic balancing)
Eliminating non-value creating utilization of energy (e.g. modify order processing)	Adjust process parameters in relation to needs
Periodic maintenance	Energy recovery
	Avoiding losses (e.g. heat insulation)
	Process, material and technology selection/substitution (e.g. replacement of drives)

3.4. Visualization and significant key figures

The variation of energy efficiency due to modified settings of the model scaled process can be shown by significant key figures or plots. The representation will include the change in energy demand and of specific productivity values, e.g. a distinction between value-adding and non-value-adding energy proportions. Visualization and key figures will help to achieve competence through depicting energy efficiency potentials even though some are not easy to perceive.

4. Case: CNC milling center

Based on the outlined approach a fully functional model scale CNC milling machine was built up with focus on electrical energy efficiency.

4.1. Design Process

To generate the foundation for the machine design following the proposed approach the start-up behavior of an industrial machining process has been metered. With the obtained load profile different components were identified, classified and evaluated regarding their energy demands. The cumulated energy demands for the three categories controls, peripherals and machining are shown in Figure 5.

Table 4: Design criteria for the model scale CNC milling machine.

Industrial scale component (relative load)	**Relevance**	**Measures**	**Redundancy**	**Scalability**	**Result**
Controls (~5%)	*Only applicable for peripheral components*				**Transformation** to model scale
Peripheral 1 (~29%)	Yes	Yes	--	No	**Substitution** with scalable handling system which has comparable impact
Peripheral 2 (~31%)	Yes	Yes	Peripheral 3	No	**Elimination** due to redundancy with Peripheral 3
Peripheral 3 (~20%)	Yes	Yes	Peripheral 2	Yes	**Transformation** to model scale
Peripheral 4 (<1%)	No	Yes	--	Yes	**Elimination** due to low relevance
Tool Spindle (~15%) *incl. machining*	*Only applicable for peripheral components*				**Transformation** to model scale

The evaluation of the identified peripheral components led to further examinations regarding the criteria outlined in the approach (see Table 4). Peripheral components have been eliminated and substituted in this step according to the introduced criteria. Subsequently, possible efficiency measures for the transfer towards the model scale were identified for the following system components: controls, exhaust air system, handling system and tool spindle. Among others, potential measures include the reduction of processing time, efficient control of peripheral systems and filter efficiency.

To be compatible with the MPS stations available today, the model scale CNC milling machine is equipped with an automated electrical and pneumatic handling system. Because the model scale machine tool is able to perform a real machining process a venturi nozzle for removing chips was added. The buildup of the model scale process is displayed in Figure 3.

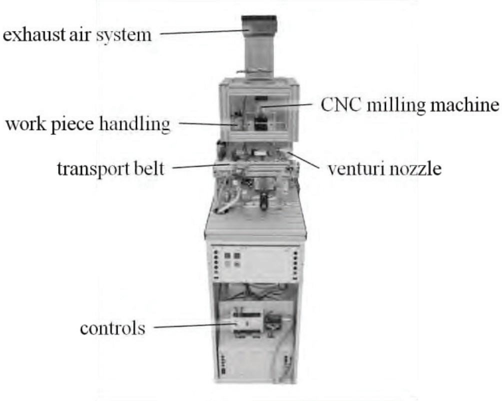

Figure 3: Model scale CNC milling machine.

The functional model scale CNC milling machine has the following electrical components:

- Festo CECC controls
- Exhaust air system with air filter
- CoolTool CNC slides and tool spindle
- Transport belt

A suitable metering concept was developed. It includes the metering of the total electrical energy demand of the whole process as well as every single electrical powered component. The detailed metering allows a direct visualization of the components' energy demand in every operating state and of the impact on efficiency measures. The pneumatic load is monitored in total as there are only three pneumatic components, each with a distinct load characteristic.

4.2. Evaluation

The functional model scale CNC milling machine was fitted into an existing process chain of Festo MPS stations. This setup has been used to evaluate the mechanical behavior of the process and the implementation of efficiency measures. The machining performance was examined with three different materials: PLA and ABS plastics and aluminum. The model scale tool is able to machine workpieces of all three materials at different speeds. Naturally, the processing time for the harder aluminum is higher than for the plastic materials.

The evaluation of the electrical load profile of the milling process shows a good correspondence to the industrial scale profile that was set as a base for the design of the model scale process. The start-up behavior of the electrical components proves to be relatively similar (see Figure 4). The elimination of peripheral components for transition into the model scale is well compensated by the exhaust air system and the addition of a transport belt. The relative electrical energy demands of the single components on model scale show a significant improved comparability to industrial scale processes. The metered energy demands of the components fit well with those of the industrial scale, real machine tool. Thus the main goal of displaying adequate energy transparency on a model scale can be achieved with the developed design approach.

Figure 4: Load profiles of characteristic industrial machining processes and model scale processes.

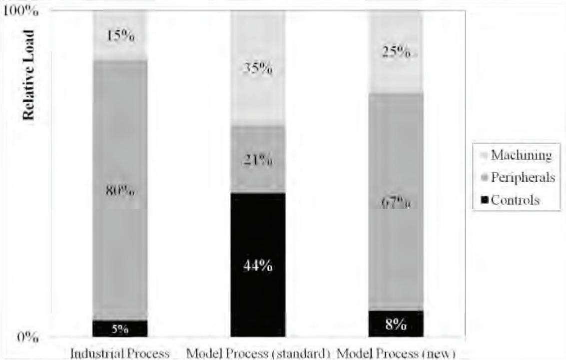

Figure 5: Relative loads of characteristic industrial processes, standard models and new model process.

4.3. User interactions related to energy efficiency measures for the model scale CNC milling center

Derived from previously stated interactions (pointed out in Table 3) and the resulting changes in energy demand, different measures could be adapted to the model CNC milling center. The impact depicts phenomena of industrial scale machine tools. An overview of implemented interactions of the model scale CNC milling machine is shown in Table 5.

Table 5: Implemented interactions to gain energy efficiency on the model scale process.

Organizational Interactions	Technical Interactions
Reduce stand-by of peripheral units (exhaust air system, removed material suction, transport belt, tool spindle)	Adjust compressed air pressure Change workpiece raw material Change flow resistance of exhaust air system Adjust suction speed of exhaust air system

The flow resistance of the exhaust air system can be manually modified by a butterfly valve inside the suction duct and the manual change of inserted filter material. The change of resistance is measured by two pressure sensors above and below the filter and the butterfly valve. Furthermore, the suction speed of the implemented fan can be directly modified by pulse width modulation. A manual interaction possibility is implemented through a turning knob. On the other hand, a link-up to the pressure sensors inside the suction duct can be made and a custom closed loop control algorithm for the suction speed of the exhaust air system can be implemented.

5. Conclusion and Outlook

A generic approach for designing model scale production processes for the competence development in manufacturing related energy efficiency was developed. Corresponding industrial scale processes and their respective load profile served as a basis. The energy demanding peripheral and process components have been identified and evaluated regarding an adequate transition into the model scale. Efficiency measures for learning and experiencing energy efficiency have been taken into account and combined with further restrictions by the surrounding infrastructure and process chain to create the design of a model scale process. The outlined approach was validated by the creation of a model scale CNC milling machine. The machine was then fitted into a learning environment for energy efficiency and evaluated in respect to the mechanical quality of the process, the transformation to model scale and the implementation of efficiency measures.

Having setup a promising technological infrastructure for energy efficiency, the next step is to focus on corresponding educational contents. The proposed approach sets the foundation for developing and implementing specific learning methods and concepts. These need to be aligned to curricula of academic and occupational contexts. In addition the model scale processes could be engaged apart from predefined user interactions to follow approaches like research-based learning.

The outlined approach and design procedure can be applied to create different kinds of model scale production processes. Thermal and handling processes and the integration into process chains will be the next samples to focus on. Furthermore, the adaption of the presented approach towards resource efficiency is desirable. One promising starting point could lie in the model scale design of closed loops for the currently processed PLA and ABS workpieces.

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