Energy efficiency in assembly systems

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Abstract

In order to provide flexibility in manufacturing many tasks are still executed manually. Tasks like assembly, cleaning, and packaging thus imply the use of workstations. Here we show the development of a method to assess energy consumption at different levels of a factory system. Exemplarily manual workstations are assessed using flexible measurement concepts. Conducting the assessment in the environment of a learning factory, energy saving potentials of up to 65 percent were identified. Besides, the findings were transferred into an interactive learning concept and a prototype workstation used in production processes for products made from CFRP was developed. We anticipate that an energy-efficient design of workstations is an example of how energy transparency in manufacturing can be increased, especially in industries that are characterized by customer-specific, low-volume production and a high share of manual operations.

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1. Introduction

Optimization measures for energy efficiency have focused on reducing the ecological impact of manufacturing operations since the late 60s. Ever since the rational use of energy and material has become an important factor for competitiveness, especially in highly developed manufacturing environments of the western world [1, 2]. Though the widespread requests in industries for short payback period’s favors the realization of energy efficiency measures in large scale machinery and production equipment [2, 3].

Yet, for instance Galitsky and Worrel identified possibilities to improve energy efficiency in the vehicle assembly industry [4]. Nevertheless workstations used in set-up, assembly, rework, cleaning, commissioning and packaging tasks have not been considered since their total energy saving potentials appear to be minor [5]. However this study presents results that show that in terms of relative saving potentials it is worth addressing aspects of energy efficiency in the design and operation of assembly systems. Moreover we show how these learnings can be transferred to other areas of manufacturing systems in the context of a learning factory on resource efficiency [6].

2. Methodology

The work is intended to contribute to the current strife for transparency in manufacturing considering energy consumption. Therefore, Fig. 1 categorizes manufacturing operations according to their contribution to energy transparency in production facilities encompassing different levels of a factory system according to systematic described in [7]. It illustrates the efforts that need to be undertaken (e.g. complexity of individual measurement concepts) in order to augment energy transparency in manufacturing operations. Fig. 1 subdivides a factory system in different levels encompassing building location, building shell, building services, auxiliary processes, machinery and processes. It shows how complexity increases alongside with the aggregated level of information. Different levels of a factory require different measurement concepts. Besides, from an economical
perspective energy transparency needs to be contrasted with investment costs for the installation and current costs for operation and maintenance of energy monitoring systems. Energy consumption transparency in manual assembly therefore is one specific approach on how to increase the aggregate level energy transparency.

Looking at the market development, the share of manufacturing facilities being specialized on final assembly is increasing in countries with high energy costs, e.g. Germany. Target Key Performance Indicators (KPIs) to be quantified in assembly planning projects are usually lead time, overall equipment efficiency or stock. In addition to that, energy demand and energy efficiency need to be considered. Therefore this paper firstly assesses an approach on how energy efficiency can be systematically assessed and optimized.

3. Development of Reference Scenarios

The analysis of assembly systems in this paper specifically addresses energy consumption. Besides aspects of work design, ergonomics and occupational safety were considered since they imply the use of operating resources such as lighting and extraction systems. Since workstations for manual activities are frequently used in assembly operations, different assembly tools are compared for their energy consumption during reference operations. In order to acquire comparable results reference scenarios were developed. Subsequently good- and bad practice solutions are compared and measurement results are presented.

3.1. Lighting
(Constant vs. presence- and daylight based control)

Speed, accuracy and reliability of visual tasks are significantly influenced by lighting levels.

The maximum lighting for the task area and the immediate surrounding can be derived from the requirements described in DIN EN 12464-1. According to the norm, the maintenance value $E_m$ for indoor workplaces depends on the conducted working operation. Commonly encountered requirements in a manufacturing environment are listed in Table 1.

<table>
<thead>
<tr>
<th>Conducted working operations</th>
<th>$E_m$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Quality control</td>
<td>1,000</td>
</tr>
<tr>
<td>Assembly tasks (very precise)</td>
<td>750</td>
</tr>
<tr>
<td>Fine machine works</td>
<td>500</td>
</tr>
<tr>
<td>Tolerance: &lt; 0.1 mm</td>
<td></td>
</tr>
<tr>
<td>Rough and average machining</td>
<td>300</td>
</tr>
<tr>
<td>Tolerance: ≥ 0.1 mm</td>
<td></td>
</tr>
</tbody>
</table>

Good practice solution for the lighting of workstations encompasses the use of presence- and daylight based control system, which turn off the light (or reduce it to a minimum lighting level required for orientation) during times of inactivity e.g. breaks or shift changes. Besides daylight control adjusts the illuminance according to daylight availability (ref. Fig. 2).

Given the before mentioned, a static scenario for the presence and daylight based control was implemented. Therefore a digital luxmeter was used to measure horizontal illuminance in the task area of an 850 mm high workplace surface (ref. Fig. 3). The reference workstation itself is situated in a representative working environment 10 m away from a window area that faces north with a height of 12 m.
The measured values for illuminance were translated to a 0-10 V control signal applied to the electronic ballast (EB) of the lighting system in order to fulfil the defined requirements of 500 lx respectively 800 lx at the workplace surface. Besides non-presence of workers was considered for standard breaks and shift changes. During this period the installed lighting fixture is dimmed to 10 % of its maximum illuminance for orientation.

The calculation of the appropriate number of luminaires for the workstation was derived from applying the lumen method described by the German Lighting Society (LiTG) [9]. This planning method considers several factors such as utilance, coefficient of utilization, lamp aging and contamination. Besides distribution curves for luminosity provided by the manufactures of lighting fixtures were considered. As a result a dimmable lighting fixture with two 18 W T8 fluorescent tubes and a luminous efficiency of 100 lm/W was selected. The power consumption of the sensor for presence and daylight detection are 0.3 W.

The measurement scenario considers two shift operation between 6:00 am and 10:00 pm for both 500 lx and 800 lx illuminance levels.

3.2. Extraction system (Mechanical throttle control vs. rotation speed control)

The second scenario addressing energy efficiency in workstation is the use of extraction systems. Extraction systems are required to assure product quality and occupational safety regulations such as the Maximum Concentration Values at the Workplace according to the MAK-Commission or maximum dust emission limits defined in the Technical Rules for Hazardous Substances (TRGS 900) by the Federal Ministry of Labor and Social Affairs [10, 11]. The second regulation defines a time-weighted average limit for the emitted particles of 3 mg/m³ for the alveolar fraction <10 µm (A- dust) and 10 mg/m³ for the respirable fraction >10 µm (E- dust). These consideration are highly relevant in production systems for CFRP products, where small particles are a byproduct of rework or finishing operations such as cutting, sawing, drilling but also polishing (ref. Fig. 4) [12].

But, extraction systems are also used in various other production processes such as casting, welding or machining, where sufficient extraction is also mandatory due to legal compliances and workers well-being. However most equipment (e.g. vans and pumps) is found to be operated in the range of 30 % - 60 % of its rated power [13]. Moreover the importance of the considered reference scenario and its wide transferability is show if we consider systems that follow the same physical principals such as air handling systems as a part of technical building services. These systems also frequently lack the use of intelligent sensor based control systems.

Therefore the workstation in the learning factory addresses the topic by comparing conventional throttle with speed control to adjust suction capacity $P_q$.

Throttle control is based on the principle that a change of differential pressure $\Delta p$ at the operating ventilator reduces the suction capacity $P_q$ and shaft power $P_V$ proportionally (1) (2).

$$P_q = q \cdot \Delta p$$
$$P_V = \frac{P_q}{\eta_G}$$

In general this is done by readjusting the conveying cross section for instance by a mechanical value. Hence the system curve $A - A'$ is steeper and the operating point moves towards smaller volume flows (ref. Fig. 5). However from an energy consumption point of view this type of control hardly changes the power consumption of the fan unit (ref. Fig. 6).

The relative power consumption of centrifugal fans at various control modes is referred to in Fig. 6.

This graph also illustrates theoretical energy saving potentials. Besides the physical relationship is described in equation (3) and (4), with $q$ being proportional to $n$ and $\eta_m$ and $\eta_G$ standing for the motor respectively gear efficiency.

$$P_V = P_{V,0} \cdot \left( \frac{n}{n_0} \right)^3$$
$$P_M = \frac{P_V}{\eta_M \cdot \eta_G}$$

Fig. 4 Distribution of particle size for different CFRP manufacturing processes [12]

Fig. 5 Operating characteristics of extraction systems with throttling and speed control (graph based on [14])
In order to analyze a representative measurement scenario we imply the findings of Hoshide on partial-load operation and assume that during 60% of its total operation the suction capacity is reduced to 70% of its maximum. No breaks or shift changes are considered.

### 3.3. Assembly tools (pneumatic vs. electric)

Besides lighting and extraction the third element demonstrated and compared for energy efficiency at the workstation is the use of different assembly tools. Therefore the use of pneumatic and electric assembly tools was compared using equal assembly operations.

In order to evaluate the findings from the measurements in a realistic use case for economical viability, the following assumptions from final assembly in car manufacturing according to Bookshar were made [15].

- 2 assembly tools per vehicle
- 60 vehicles per hour
- 16 hours per day
- 5 days per week
- 50 weeks per year

Besides a threaded plate for 24 equal screwing operations was designed for being used interactively in the learning factory (ref. Fig. 7)

### 4. Results

In this section the results of the measurements are presented. Those were conducted using flexible measurement systems with a sampling rate of 50 kHz per channel for both current and voltage at a resolution of \(\Delta U = 2\,\text{mV}\) at voltage levels of 0 – 10 V [16]. The compressed air consumption was measured using a thermal mass flow meter designed for maximum air flows of 600 l/min with an output signal between 0 – 10 V.

#### 4.1. Lighting

This section compares four different lighting scenarios and presents their respective energy saving potentials. Scenario 1 compares energy consumption of conventional and daylight based control for illuminance requirements of 800 lx. The calculated saving potentials presented in Fig. 8 are 18% compared to conventional control. Applying both presence and daylight based control the power consumption for the reference scenario is 431 Wh compared to 566 Wh resulting in energy savings of 24% (ref. Fig. 9).
of 44% for daylight and 47% for daylight and presence based control (ref. Fig. 10 and Fig. 11).

Considering 4,000 working hours the annual energy costs for lighting at the described reference workstation are 21.20 € (implying 15 cents/kWh) in the conventional configuration. Applying daylight and presence control these costs can be reduced to 11.40 €/year (including energy consumption of the required sensors).

Lighting requirements determine energy consumption of lighting systems for a great part. Yet here we show that the choice of illuminants and their demand-oriented control can be implemented as a measure to increase energy efficiency during design or retrofit of workstations. Considering the cost for the new florescent lamps (40 €) (+ 10% of the investment costs for maintenance), low loss ballast (40 €) and sensor module for presence control (150 €) (one module serves 10 lighting fixtures) results in a return on investment (ROI) of 3.5.

4.2. Extraction system

For the demonstration of energy saving potentials in extraction systems an industrial vacuum cleaner with a nominal power consumption of 2.2 kW was customized for speed control using a frequency converter. The converter in use is designed for an asynchronous motor with a capacity of 2.2 kW, 400 V and a rated current of 6.4 A. Power losses of the frequency converter are specified in the data sheet with 92 W. The maximum volume flow rate of the vacuum cleaner is 270 m³/h. Considering the scenario described in 3.2 the active power of at the asynchronous motor is measured by recording current and voltage at all three phases (L1, L2, L3). The electrical power consumption of the vacuum cleaner for the scenario described in 3.2 is presented in Fig. 12. Results for both speed and the throttle control are shown. The difference in absolute power consumption as a result of the reduction of the volume flow becomes apparent. For example, while lowering the flow rate to 141 m³/h (60% of the maximum volume flow) through throttle control, the power consumption is 1,544 Wh for continuous operation during one hour. Yet, with speed control the consumption is only 517 Wh, corresponding to an energy saving potential of 66% or energy cost savings of 616 € a year. Considering the scenario with the respective number of changes in volume flow rate the annual energy-saving potential are still 27% representing cost savings of 267 € a year for the described scenario.

Reviewing the recorded load profile the different characteristics of the power curves for both control methods are apparent. While high starting currents occur for speed control as a result of acceleration of the asynchronous motor, no such peaks are detectable for throttle control. Frequently alternating loads can therefore affect the energy costs. In general, the operation of motors in unfavorable partial load results in a loss of efficiency, due to higher heat losses in the motor and additional losses of the frequency converter. Yet, since the motor power reduces relatively by the third of the rotational speed, significant energy savings can be achieved, especially for systems that operate long periods in a load-reduced range. Considering the costs for retrofit of a frequency converter (+10% of the investment costs for maintenance) the ROI is 0.5.

4.3. Assembly Tools

In this section an electric baton screw driver and a pneumatic screwdriver designed for max. tightening torque of 3.0 Nm and a rotational speed of 1,000 min⁻¹ are compared. The
electric baton screwdriver requires a supply voltage of 36 V. The pneumatic screwdriver requires 6 bar operating pressure and its nominal air consumption is 278 l/min. In order to contrast energy consumption of electric and pneumatic tools we assume a system for compressed air supply consisting of a compressor with a maximum air supply of 1,200 l/min. and an operating pressure of 7.5 bar. The connected load of the entire system is 7.81 kW, of which the electric motor accounts for 7.5 kW and the refrigerant dryer for 0.31 kW.

Based on these characteristics, the energy costs can be calculated per consumed cubic meter of air. At an electricity price of 0.15 €/kWh and an assumed motor efficiency of 93 % it is 0.015 € per 1000 liter. Besides, we assume that in a representative assembly environment the pneumatic assembly tools are responsible for 20 % of total air consumption.

For the assembly operation described in 3.3 the measured air consumption of the pneumatic tool is shown in Fig. 13.

Fig. 13 Air consumption of pneumatic screwdriver

In average it is 4.54 liter per assembly task. Considering average losses in a compressed air system of 5 % the use of pneumatic tools implies constant 24/7 losses of 20.70 l/min.

Fig. 14 Energy consumption electric tool

Thus the annual costs for the use of the described air tool consist of 10880 m³ for losses and 8717 m³ for the described screwing operations resulting in a total of 314 €/a.

By contrast the electric tool consumes 8.8 W in standby or 77,438 Wh a year and 27,893 Wh a year for the screwing operations exemplarily measured for 24 cycles in Fig. 14. This represents annual electricity costs of 15.80 € or 313 € (95 %) annual cost savings compared to the use of the pneumatic tool.

The standby consumption due to standby losses in the compressed air system and the power supply unit is predominant for both cases. In case of air and is 58 % for the pneumatic tool and 74 % for the electric tool. The replacement costs for the pneumatic tool are about 1,000 €, thus resulting in a ROI of 3.8.

5. Integration in a learning factory

The developed scenarios have been integrated in the environment of a learning factory on resource efficiency. The process chains used for demonstration purposes in the Green Factory Bavaria follows the production steps for lightweight products made from carbon fiber reinforced plastics (CFRP).

The main objectives of the learning factory are to develop consciousness for aspects of energy and material consumption in production environments and to train students and industrial practitioners in methods and practices on how to increase resource efficiency in existing and newly developed products and production facilities. Fig. 15 summarizes the learning concepts implemented in the assembly system used for mold confectioning, ply placement, cleaning and polishing purposes in the process chain of the Green Factory Bavaria.
6. Conclusion and Outlook

In conclusion it could be shown that the energy efficiency of workstations, including lighting, extraction and assembly as well as their presentation in the environment of a learning factory offer multiple opportunities to transfer knowledge to industry practitioners. Effects shown in small can be transferred into various applications in industry and therefore contribute to a distribution of knowledge on sustainable manufacturing practices [17].

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