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4.3 Interdependencies between energy productivity and target figures of lean production systems

P. Schnellbach, G. Reinhart

Fraunhofer IWU – Project Group Resource-efficient Mechatronic Processing Machines, Augsburg, Germany

Abstract

Energy productivity will be a significant competitive advantage for manufacturing companies in future. Therefore, a methodical approach is necessary to identify potential in manufacturing and reduce energy waste. In order to develop this approach, it is obligatory to consider interdependencies to established production systems. Starting with Toyota, car manufacturers were pioneers for the implementation of Lean Production Systems (LPS). Their production processes are measured by LPS target figures like quality or through-put time. Efforts to raise energy productivity can cause impacts on existing production processes and therefore result in interdependencies with LPS target figures. The methodology presented in this paper helps to increase energy productivity under consideration of these interdependencies. The so called House of Energy Productivity is introduced as one important part of the methodology.

Keywords:

Lean Production, Energy Productivity

1 INTRODUCTION

Coming from the background of a worldwide shortage of resources, a wise consumption of energy has become a main issue for governments as well as manufacturing companies. With 31 % of primary energy use, manufactures are one main consumer of energy [1]. That high proportion of usage leads to a certain responsibility for energy waste reduction. Important drivers like rising energy prices, new environmental regulations with their associated costs for CO_2 emissions and changing customers' behavior with regard to green products must be considered by manufacturers in the short run. An efficient and effective use of energy can make a high contribution towards energy waste reduction [2]. Besides other resources, energy in manufacturing is therefore an important field for both science and industry.

Starting with Toyota, car manufacturers were pioneers for the implementation of Lean Production Systems (LPS) in the last decades. By doing so, they succeeded in improving target figures like lead time, quality and cost [3]. Reduction of energy waste in manufacturing was not of great concern at that time and is therefore not described as a part of LPS [4]. Already existing and established LPS structures in turn can help integrating energy productivity aspects in manufacturing companies sustainably [5], [6]. However, by implementing a structured proceeding to reduce energy waste, possible interdependencies to LPS target figures have to be considered. Otherwise the combination of lean and green measures can have unexpected impacts on production [7].

Therefore, the Project Group Resource-efficient Mechatronic Processing Machines (RMV) of Fraunhofer IWU started to develop a methodical approach to increase energy productivity in car manufacturing while considering interdependencies to LPS target figures. This paper presents the so called House of Energy Productivity (HoEP), which is part of that methodical approach. The paper starts with a definition of energy productivity in manufacturing and a description of important target figures in LPS. Guidelines to increase energy productivity are derived from the state of the art literature and integrated in the HoEP. The guideline example *recuperation* shows the usage of the HoEP and reveals direct impacts of measures on electrical power and time.

2 ENERGY PRODUCTIVITY AND TARGET FIGURES IN LEAN PRODUCTION SYSTEMS

2.1 Definition of energy productivity in manufacturing

The term energy productivity is often used to measure the performance of national economies quantified as the gross domestic product (GDP) divided by the nation's energy consumption [8], [9]. In manufacturing the term energy efficiency is more common, generally measured as the useful output of a process divided by the energy input [8], [10]. Although the quantification in both cases is output divided by input, and both terms are often used as synonyms, there are reasons to make a difference. [11] define the term *productivity* as social concept and as an *attitude of mind* strongly combined with the continuous improvement process. Productivity tries to improve already existing things continuously in order to become better every day. [12] states that productivity is commonly defined as efficiency (outputs over inputs) plus effectiveness (outputs relative to a standard or goal). By combining both terms, productivity can be defined as [11]:

$$\textit{Productivity} = \textit{Efficiency} + \textit{Effectiveness} \\ = \textit{"Doing the things right"} + \textit{"Doing the right things"} \quad (1)$$

These perceptions can be translated to energy productivity in manufacturing as well:

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Energy productivity is hereby seen as an attitude of mind to improve the ratio of useful output divided by the energy input. On company level it is measured by output or value added e. g. in form of sales divided by the energy input e. g. in form of total energy cost [13]. On shop floor level energy intensity (the inversion of energy productivity) is measured as the energy use divided by a unit of industrial output, e. g. kWh/car [1], [2], [9]. Energy intensity is used on shop floor level in order to make energy demand more tangible for workers.

With these measurements on company as well as on shop floor level, energy effectiveness is not considered so far. Effectiveness is defined as a measurement of outputs compared with goals [12]. Correspondingly, it can be translated as *Doing the right things* as mentioned before [11]. In case of energy productivity in car manufacturing, the *right things* are considered as measures to reduce energy waste either without negative impact, or with positive impact on existing manufacturing structures. Especially in car manufacturers' industry these structures are strongly designed by LPS [14]. The overall performance of LPS is reflected in target figures like quality or lead time [15].

To sum up, energy productivity in manufacturing is defined as an attitude of mind to reduce energy waste continuously through energy waste reducing measures considering the impact on LPS target figures.

2.2 Target figures in Lean Production Systems

LPS are defined as "enterprise-specific compilations of rules, standards, methods and tools, as well as the appropriate underlying philosophy and culture for the comprehensive and sustainable design of production" [16]. They consist of principles, methods and tools and have their origin in the Toyota Production System (TPS). TPS was developed by Toyota in Japan in the middle of 20th century. In 1990 it was revealed through a study published by the International Motor Vehicle Program (IMVP) of Massachusetts Institute of Technology (MIT). The study presented a Japanese manufacturing concept, which was superior to the manufacturing concepts of American and European car manufacturers. It became popular as *Lean Production* [3].

Instead of going for *make-to-stock*, Toyota implemented the principle of *Just-in-Time* as one pillar of the TPS, which is often shown in form of a house. The second pillar was called *Jidoka*, which is also known as *autonomation* – the ability for production machines to stop autonomously in case of manufacturing defects. The basement of the TPS house was built by the continuous improvement process (CIP), also known as *Kaizen*, which was concentrated on eliminating waste by continuous step-by-step improvements [17]. In order to do so, Toyota defined seven types of waste like over-production, inventory or waiting. Different lean methods like *Kanban* or *Poka Yoka* helped to implement the principles of the TPS in production [3], [18]. After the publication of the IMVP study, American and European car manufacturers started to adapt the TPS and implemented it in their own company [14]. Today these production systems are generally known under the term *Lean Production System* (LPS) [4].

After measuring the performance of manufacturing usually with the target figure cost in the past, several other target figures are common in LPS today [15], [19]. From a state of the art research, four important target figures have been chosen to measure the performance of the LPS in car manufacturing and to visualize the impact of energy productivity on LPS. These four target figures are flexibility, lead-time, productivity and quality. Since every mentioned target figure can be derived monetarily, they have an indirect impact on cost. Therefore, cost is not considered as separate target figure in the presented methodology [20]. Table 1 shows the quantification of the chosen target figures.

Target Figure	Quantification
flexibility F	$F = \frac{\#\,res}{\#\,var} \times \frac{wt}{(pb \times pt) + ct}$ with # res: number of same resources # var: number of variants wt: daily working time pb: average production batch pt: processing time ct: changeover time
lead time L	L [time unit] = time of distribution − begin of processing
productivity P	$P\,[\%] = \frac{\text{production output}}{\text{maximum production output}} \times 100$
quality Q	$Q\,[\%] = \frac{\text{zero defects products}}{\text{production output}} \times 100$

Table 1: Quantification of target figures, adapted from [20].

In order to reduce energy waste in manufacturing considering interdependencies on LPS target figures, an analysis to expose these interdependencies is necessary.

2.3 Interdependencies between energy productivity and LPS target figures

Interdependencies between measures to increase energy productivity and LPS target figures are obvious as the following example points out. An oven used for a drying process would not utilize its full capacity in order to create a single-piece flow. Coming from an energetic perspective, the energy intensity of the process could be reduced by changing the single-piece flow principle into a batch production. By doing so, the full capacity of the oven could be used and less energy would be wasted to dry the products. On the other side, a change from single-piece flow to a batch production could result in a longer lead time (Figure 1).

Besides the impact on lead time, there are possible impacts on other target figures, too. The simple example from Figure 1 shows the requirement for an intense analysis of interdependencies on LPS target figures. Therefore, it is necessary to develop a methodology, which

- helps to identify energy productivity potential in a defined manufacturing area,
- offers concrete measures derived from guidelines and adjusting levers to increase energy productivity,

- considers interdependencies between energy productivity measures and LPS target figures and
- gives recommendations to decide, which measures should be implemented or not.

Every bullet point describes one part of the whole methodology. The second part in order is the HoEP, which is explained in this paper.

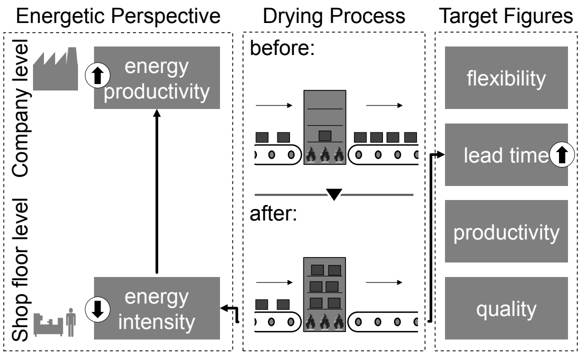


Figure 1: Interdependencies between energy productivity and lead time through the change of a drying process.

3 HOUSE OF ENERGY PRODUCTIVITY

The HoEP (Figure 2) is one important part of the methodology. It helps to derive concrete measures to improve energy productivity respectively to reduce energy intensity. The preliminary work to build up the HoEP, its important components and its application are described in the following chapters.

3.1 Development approach and preliminary work

In order to develop the above mentioned methodology, general possibilities to increase energy productivity have been investigated in a preliminary work. Therefore, a 3-step approach has been created. First step is the definition of guidelines for possible energy productivity potential. In a second step, the guidelines lead to adjusting levers, which can be classified into an energy productivity portfolio to visualize possible impacts. Guidelines and adjusting levers build important components of the HoEP and help to generate concrete quantifiable measures to reduce energy waste in a third step.

3.2 Components of the House of Energy Productivity

Energy productivity guidelines are an important component of the HoEP. While giving orientation to identify energy waste potential on an abstract level, they are comparable to the seven types of waste in LPS [16], [18]. The procedure to define the guidelines is visualized schematically in Figure 3. At first the existing literature was analyzed for the state of the art guidelines. Several other terms like *general approaches* or *energy efficiency principles* are used in the same sense and were considered during the research as well. As a result, 15 different references with overall 159 guidelines were identified. Next step was a reduction by eliminating those, who didn't fit one of the following criteria.

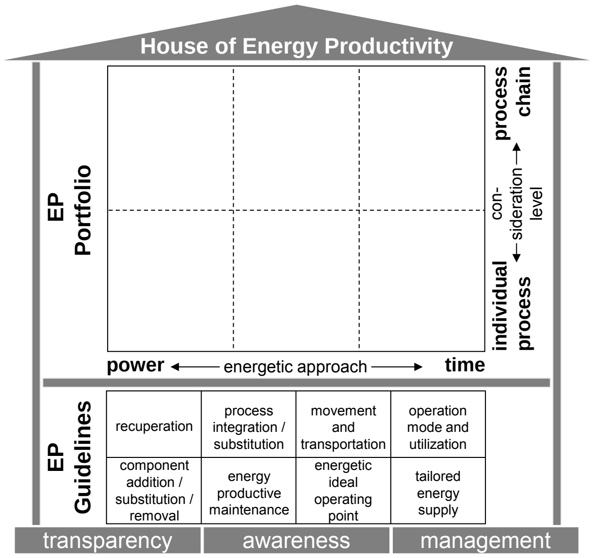


Figure 2: House of Energy Productivity.

In terms of energy economics, only guidelines which handled net energy were considered [21]. Furthermore, the guidelines had to be applicable to car manufacturing industry. Besides, only guidelines which referred to operating phase and therefore to the CIP during product life cycle were considered. The last elimination criterion was related to the guideline's energy cost leverage. The two charges, which can be affected directly in manufacturing, are the energy charge (price based on the energy consumed within a certain time frame expressed in kWh) and the power charge (price based on the peak expressed in KW) [22]. As the possible impact on peak loads is limited on a shop floor level, for the developed methodology the energy charge was considered as cost leverage exclusively. Guidelines, which address peak loads, should be considered in a companywide peak load management, which is not part of the developed methodology. Furthermore, some guidelines fit the criteria, but would not lead to concrete quantifiable measures. Such guidelines refer to transparency, awareness and managerial structures to support the energy productivity improvement process. They were separated from the rest and summarized within one basic principle building the basement of the HoEP.

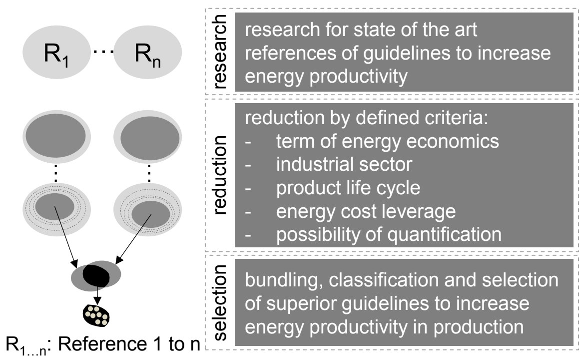


Figure 3: Procedure to define energy productivity guidelines, adapted from [23].

After the step of reduction, the 66 remaining guidelines were bundled and classified to eight superior guidelines which are shown in Figure 4.

recuperation	process integration / substitution	movement and transportation	operation mode and utilization
component addition / substitution / removal	energy productive maintenance	energetic ideal operating point	tailored energy supply

Figure 4: Energy productivity guidelines.

From every guideline, several adjusting levers can be derived. They differ from the guidelines in their level of detail. Considering the elimination criteria mentioned above and using the guidelines as orientation, adjusting levers are possibilities to increase energy productivity, while showing their direct impact on energy consumption. In order to do so, an energy productivity portfolio was designed with two dimensions (Figure 6).

On the ordinate, the consideration level is shown. The differentiation is between an individual production process, which consists of a certain technology and the manufacturing equipment [24], and a process chain, which consists of different individual processes. Adjusting levers, which have impact on one individual production process only, are positioned in the lower area of the portfolio. Levers, which affect more than one process, are positioned in the upper area.

The abscissa shows the energetic approach of the levers. Generally energy is quantified by the multiplication of electrical power and time [10], [25]. Therefore, every energy productivity measure, which is generated out of an adjusting lever, either has an impact on electrical power (left area of the portfolio), on time (right area of the portfolio), or on both (medium area of the portfolio). As LPS target figures are mainly time driven (Table 1), a position on the right area of the portfolio results in a higher impact level.

Every impact on electrical power causes a change in efficiency η defined as ratio obtained from target energy flows supplied and energy flows used in an individual process or a process chain in the stationary state [21]. Every impact on time can be directly quantified with help of production time recording models, such as the occupation time model of [26]. Therefore, every adjusting lever must be assignable to one of the six areas of the portfolio to reveal its direct impact on energy. From the state of the art a defined number of adjusting levers can be deviated and documented. The procedure for the identification of the levers is presented exemplarily in the next chapter. With the knowledge of their impact on energy, the adjusting levers can be used to identify concrete measures in a defined manufacturing area.

The energy productivity portfolio, the guideline table and the basic principle (transparency, awareness and management) are the important components to build up the HoEP (Figure 2). The application of the HoEP is exemplified with the help of the guideline *recuperation*.

3.3 Exemplary application of the HoEP with the guideline *recuperation*

The origin of the term *recuperation* is the Latin verb *recuperare*, which means *recover* or *regain*. In the HoEP, the guideline *recuperation* is defined as general term for the approaches recovery, insulation and storage of energy. Possible measures, which can be found in literature, are

- recovery of braking energy e. g. from electric actuation [27],
- use of waste heat, resulting from the production process [25], [28],
- storage of energy loss for a later utilization on demand [28] and
- sustainable insulation of wiring, pipes and machine parts in order to avoid energy loss in production processes and during energy transfer [25].

The sustainable insulation must be distinguished from continuous actions to identify and reduce leakage losses e. g. from compressed air. Such actions are covered by the guideline *energy productive maintenance*.

Considering the elimination criteria, the possibilities for *recuperation* in production phase are restricted. The later enabling of a machining center to recover braking energy during production phase doesn't amortize and should be considered in production planning phase instead [27]. From the state of the art literature, it comes to the two possible adjusting levers heat recovery and sustainable insulation. Storage of energy loss is seen as a variation of heat recovery. For sustainable insulation the position on the ordinate of the portfolio depends on whether a single production process (e. g. a single machine center or parts of it) is affected (lower portfolio area), or a whole distribution network with several processes is affected by the insulation (upper portfolio area). In case of heat recovery, the ordinate position depends on whether the gained energy is used within the same process, where it was recovered (primary), or in another process (secondary) [29]. Primary use is positioned in the lower portfolio area, whereas secondary use belongs to the upper portfolio area.

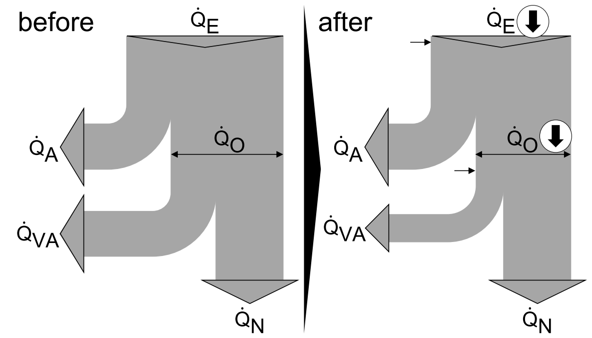
In order to determine the portfolio positions on the abscissa, possible changes in efficiencies of stationary states are proved. The technical term energy efficiency η_{en} is the sum of the thermal efficiency η_{th} and the machinery-specific efficiency η_{at}.

$$\eta_{en} = \eta_{th} + \eta_{at} \tag{2}$$

The thermal efficiency η_{th} is calculated by the ratio of the machinery-specific input power $\dot{Q}_O$ and the input power $\dot{Q}_E$. The machinery-specific efficiency quantifies the ratio of the output power $\dot{Q}_N$ and the machinery-specific input power $\dot{Q}_O$ [29].

$$\eta_{en} = \frac{\dot{Q}_O}{\dot{Q}_E} + \frac{\dot{Q}_N}{\dot{Q}_O} \tag{3}$$

Figure 5 exemplifies the impact of an insulation of a drying process to reduce the indirect power loss $\dot{Q}_{VA}$ in terms of a wall loss. The insulation causes a reduction of $\dot{Q}_O$ and thus of $\dot{Q}_E$. With constant $\dot{Q}_N$ the machinery-specific efficiency η_{at} grows. In case of *recuperation*, both heat recovery and sustainable insulation have an impact on energy efficiency η_{en} and accordingly on electrical power.



with

$\dot{Q}_E$: input energy per time (input power)

$\dot{Q}_A$: direct power loss during generation of useful energy

$\dot{Q}_O$: machinery-specific input energy per time (machinery-specific input power)

$\dot{Q}_{VA}$: indirect power loss, e. g. cooling water enthalpy, wall loss, …

$\dot{Q}_N$: output energy per time (output power)

Figure 5: Impact of an insulation of a drying process on the energy efficiency η_{en}, adapted from [29].

Hence, none adjusting lever can be positioned in the right area of the portfolio, where only time is affected. By proving the impact of recovery and insulation on time e. g. with an occupation time model [26], it becomes clear, that there are adjusting levers, which cause impacts on both electrical power and time. A heat recovery which is used to reduce the ramp-up time of a drying process can be given as example.

With this information, eight adjusting levers can be deviated from the guideline *recuperation* and positioned into the energy productivity portfolio (Figure 6).

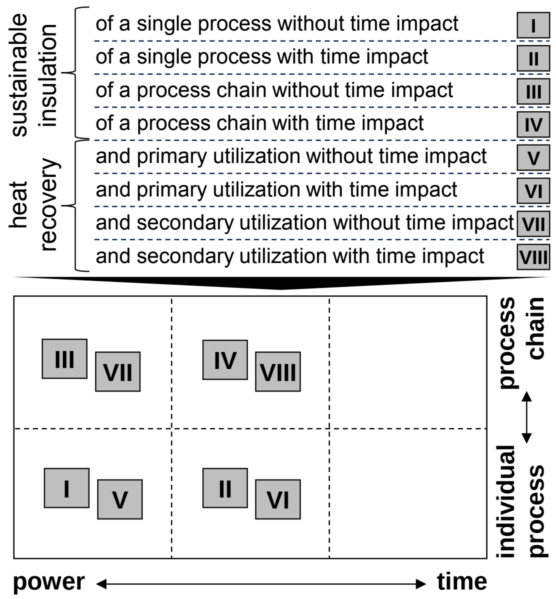


Figure 6: *recuperation* adjusting levers positioned into the energy productivity portfolio.

Completed by the adjusting levers of the other seven guidelines, the portfolio helps to identify concrete measures and at the same time makes their direct impacts on electrical power and time comprehensible. Thereby, the necessary fundament is established to identify interdependencies to LPS target figures.

4 CONCLUSION AND OUTLOOK

After pointing out the significance to reduce energy waste in manufacturing, the paper defines the term energy productivity as an attitude of mind, which combines efficiency and effectiveness, to reduce energy waste continuously through measures considering impacts on important LPS target figures. Therefore, a four step methodology was developed.

One important part of the methodology is the HoEP, which helps to generate concrete energy productivity measures through a 3-step approach. By means of revealing general possibilities to increase energy productivity, eight guidelines were derived from state of the art literature. With the guideline *recuperation*, the procedure to position adjusting levers into an energy productivity portfolio was exemplified. The portfolio defined the direct impact on electrical power and time.

Starting from the HoEP, further parts will be developed to complete the whole methodology. Upstream to the HoEP and first part on order is an adapted version of the energy value stream [13], which delivers the necessary energetic transparency to reveal energy productivity potential. Downstream, the third part is a standardized method to visualize and quantify existing interdependencies to LPS target figures, which will be identified from the fundament of deviated adjusting levers. Therefore, possibilities to visualize and quantify such interdependencies are evaluated. One possibility to do so will be the system dynamics approach, which is generally used to simulate effects from defined actions in complex systems with help of qualitative and quantitative models [30]. The final part of the methodology will be a standard procedure to give recommendations for the realization of energy productivity measures.

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