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Paper Machine Production Efficiency as a Key Performance Indicator of Energy Efficiency

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Energy is both a resource and a saleable product in the pulp and paper industry. In a highly volatile energy market, an operating strategy that maximises profitability has to be flexible in terms of making a trade-off between maximising production and minimising production costs. Profitability is therefore sensitive to changes in energy efficiency as a metric that quantifies the relationship between production and energy consumption. In this paper we present how the production efficiency of a paper machine relates to energy efficiency. We discuss the classification of time and the relationship between production rate, energy efficiency and profitability to develop key performance indicators for energy efficiency.

1. Introduction

Energy efficiency is often expressed with the following ratio (Patterson, 1996)

$$\text{Energy efficiency} = \frac{\text{Useful output of a process}}{\text{Energy input into a process}} \tag{1}$$

The energy efficiency of a large industrial process is never constant over time. Understanding the cause-and-effect relationships between the internal and external variables affecting the energy efficiency is therefore a prerequisite for the management of energy efficiency in day-to-day operations.

In this paper we approach the development of key performance indicators (KPI) for energy efficiency from the perspective of operational improvement. The purpose of the KPIs is setting targets and monitoring progress towards these targets (Hooke et al., 2004). We evaluate the applicability of the existing definitions for paper machine production efficiency as KPIs of energy efficiency, and discuss the relationship between the energy efficiency, production rate and profitability for the development of possible new KPIs.

2. Paper machine production efficiency

The overall equipment effectiveness (OEE) is a KPI of total productive maintenance (TPM) (Nakajima, 1989). The OEE measures losses due to the availability, performance rate and quality rate of the production equipment (Mätäsniemi, 2008). In the paper industry, the OEE metrics are applied in a sector-specific form. The same initial data can be used for both the production efficiency of paper machines and the OEE (Airola et al., 2005). The major difference between the two is that the production efficiency does not include metrics to describe the performance rate. In the following, we discuss the applicability of production efficiency as a KPI of energy efficiency. Figure 1 presents the definitions of the paper machine production efficiency according to Zellcheming Merkblatt III/05 guidelines.

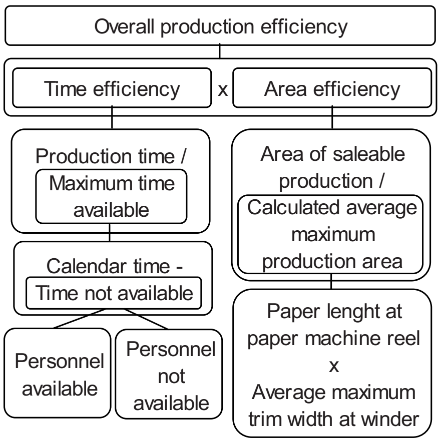

Figure 1. Definitions of paper machine production efficiency

The production efficiency quantifies the production losses related to the different uses of time and the quality of the end-products. The area efficiency has a straightforward implication for the energy efficiency: the energy efficiency increases as the area losses decrease. With the time efficiency, the situation is more complex. The time efficiency describes the opportunity to have more time available for production, as opposed to time for grade changes, breaks and maintenance. It is not obvious that an improvement in the time efficiency leads to an improvement in the energy efficiency over time because the specific energy consumption in the production time is sensitive to the produced paper grade and the production rate. These variables can have a non-linear correlation with the energy efficiency. However, we may treat the use of the available production time as a separate optimisation problem (e.g. which grade to produce, which production rate to use, and the option of not to produce). In this respect, an improvement in the time efficiency is explicitly in favour of the energy efficiency since an improvement of the time efficiency cuts back the energy consumption during downtime.

The correlation between the production volume and the energy consumption can usually be easily identified from process data during production. During downtime, the energy consumption is considerably reduced and depends on the type of production break and the prevailing external and internal conditions (Alanen, 2000). The energy efficiencies over time are therefore not comparable unless the energy efficiency in different operating situations is handled in separate accounts. The existing definitions of total production efficiency can be used for identifying these operating situations.

3. Relationship between production rate and profitability

Operational control at a paper mill has traditionally been based on a rough capacity plan where each paper grade or a grade group is assumed to be produced at a certain machine-specific capacity. In the following, we assume that the momentary production rate of an individual production run can be controlled, provided that this fits into the overall production plan. Hence, the production rate is treated as a means of manufacturing flexibility (see e.g. Hallgren and Olhager, 2009).

Changes in the energy efficiency affect the profitability of papermaking through the production costs. These, together with the sales price and the production rate, determine the profit P as follows

$$\max P = \max\left[r\left(S\text{-}C\right)\right] \tag{2}$$

where r is the production rate (tonnes per time unit), S is the sales price per tonne and C is the sum of all the variable costs per tonne. Equation 2 applies to momentary production and does not include the fixed and capital costs or storage capacity. The variable costs and the production rate form an optimum at a certain operation point. Its location depends on a number of variables, e.g. the produced paper grade and the market price.

From Equation 2 it follows that profitability is highest when operating at maximum capacity whenever there is a large profit margin between the sales price and the variable costs (case a in Figure 2). If the variable costs increase as a function of the production rate and the profit margin is low, there might be a trade-off between the optimal production rate and the variable costs, even below the maximum capacity (case b in Figure 2). In a situation where the variable costs are higher than the sales price, e.g. due to over capacity, the paper machine is operated at a production rate that reduces the production costs below the sales price to a new optimal level, until a point is reached where the paper machine is shut down. Both operations reduce over-capacity in the market.

When there is a low margin between the sales price and the production costs, the profitability is very sensitive to changes in the energy efficiency and the energy price (case c in Figure 2). Energy conservation has a high economic impact at maximum capacity since the variable costs are multiplied by the production rate. During a period of over-capacity, the energy efficiency improvement is particularly profitable since it gives a possibility to find a new optimum between the production rate and the variable costs until the maximum capacity is reached (case d in Figure 2).

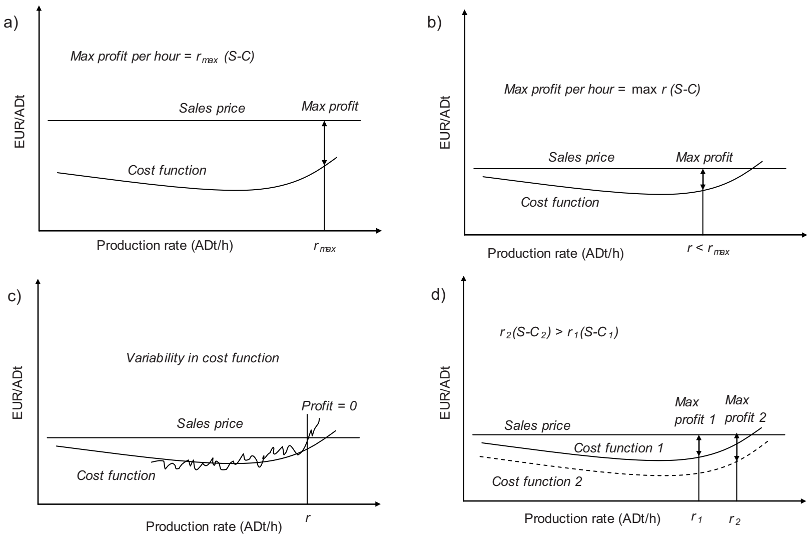

Figure 2. a) A profitable paper machine, b) profitable production during over-capacity, c) an example of variability not modelled in the cost function and d) benefits of cost reduction; ADt refers to air dry tonne of paper

The behaviour of energy efficiency should be modelled in detail in the cost function to adjust the production rate to maximise profit. Today, decisions affecting this opportunity are made already in the production planning based on assumptions that may not apply if the variable costs rise towards the maximum capacity and there is a low profit margin. The operating personnel should at least be aware of the correlation between energy efficiency and profitability to be able to adjust the production rate and to be motivated to carry out energy conservation measures.

4. Case examples

4.1 Correlation between production rate and energy consumption

Figure 3 shows the specific steam consumption of a case paper machine as a function of the momentary production of base paper by paper grade. The base paper is used as a reference even though the paper machine produces coated papers. This is done because the steam consumption in the dryer section is not linear to momentary production, the amount of coating varies by paper grade, and in coating the steam consumption is linear to the amount of coating. The use of electricity and fuels in coating is not included. The specific heat consumptions are estimated in relation to the mean specific heat consumption at the dryer design point 40 ADt/h.

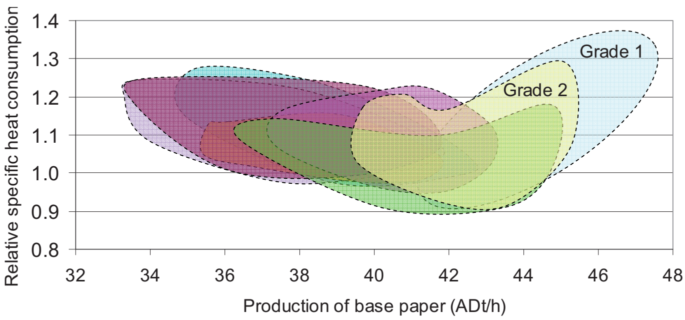

Figure 3. Specific steam consumption by paper grade in the case paper machine 2007

With grades 1 and 2 the specific steam consumption increases as the production increases. This is caused by using a higher drying rate than designed and is achieved by using elevated temperatures and excess air. Lowering the machine speed improves the energy efficiency, although it may not necessarily be profitable. Grades 1 and 2 are in production for over 20 % of the production time. Measures to reduce the specific energy consumption should be considered. The lowest specific steam consumption is achieved at 42.5 ADt/h.

4.2 Effect of downtime energy consumption on monthly energy consumption

Table 1 presents the heat consumption during breaks and shutdowns in the case paper machine. Averaging causes the heat consumption to be overestimated because the exact beginning and end of the breaks and shutdowns are only traced by the hour. Apart from this bias, Table 1 exemplifies the effect of downtime energy consumption on the total energy use over calendar time.

Table 1. Heat consumption during breaks and shutdowns compared to monthly total heat consumption in the case paper machine 2007

Month in 2007	Dryers %	Machine hall ventilation %	Shower water %	Supply air %	Steam box %	Middle pressure steam %	Total %
January	3.7	1.8	0.9	0.2	0.5	0.5	7.6
February	4.7	6.1	1.3	0.3	0.7	0.8	13.8
March	3.9	2.9	1.2	0.3	0.5	0.5	9.3
April	3.2	0.4	0.8	0.2	0.5	0.4	5.6
May	3.6	1.6	1.2	0.2	0.5	0.4	7.6
June	6.6	0.0	1.4	0.5	1.1	0.7	10.3
July	7.6	0.0	2.0	0.6	1.4	0.8	12.5
August	6.5	0.0	1.5	0.4	1.1	0.7	10.3
September	5.0	0.1	1.2	0.4	0.8	0.6	8.0
October	4.2	0.6	1.6	0.3	0.7	0.5	8.0
November	4.1	0.7	0.9	0.3	0.6	0.4	7.0
December	5.1	1.5	1.3	0.3	0.8	0.6	9.6

5. Conclusions

The following conclusions can be drawn for the development of the KPIs for energy efficiency from the viewpoint of production efficiency: 1) the relative importance of energy conservation measures increases with the production rate, 2) the existing definition of the area efficiency is suitable as a KPI of energy efficiency because it has a direct effect on the energy efficiency, 3) even though the time efficiency describes the utilisation purpose of time, not energy efficiency, it can be used as a KPI of energy efficiency provided that the energy consumption during the production time is handled as a separate optimisation problem, 4) the possible non-linear behaviour of energy efficiency as a function of the production rate can be used as a means of operational flexibility to maximise profit, and 5) the energy consumption during production, breaks and shutdowns should have separate accounts in energy reporting by using the existing definitions of production efficiency as identifiers.

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