Automatic determination of pumping system energy efficiency with EFEU software tools

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Abstract

Efficient Energy Use (EFEU) program has been founded in 2011 to assess industry-level problems in energy efficiency in Finland. The current focus is in improving fluid handling systems with systems-level approach to their design, selection and control. This paper focuses on developed software tools that allow the correct selection of fluid handling system components and control scheme based on the actual process needs throughout the typical operating cycle.

Since several existing pumping and fan systems are operating in different conditions than for which they have been originally selected, their replacement with more efficient and more suitable ones is one of the steps to more energy efficient fluid handling systems. However, one of the practical problems with existing selection programs is their focus on single device (pump, motor, frequency converter) at a time and the device selection only based on few known operating points (i.e., typical and maximum flow rates). Pumping System Optimization Tool (PSOT) was developed to solve these issues, and it allows the selection of the most energy efficient fluid handling system based on the given process needs for the flow rate and head. Matlab-based PSOT is especially usable for detailed energy audits and comparisons when device replacements are carried out in existing systems.

For throttle-controlled fluid handling systems, information on the available energy saving potential with variable-speed operation is often sufficient basis to start a more detailed analysis of system energy efficiency. Since PSOT is too detailed for this kind of preliminary analysis, Savings Calculator for Centrifugal Pumps (SCCP) was developed. It is an Excel-based software and able to estimate the fluid handling system operation accurately with a small number of input parameters and with given process needs for the flow rate. Based on other similar programs, SCCP uses more accurate models for the electric motor and frequency converter efficiency. Also the use possibility of available process data is an addition compared to other existing programs.

As these programs have a bit different calculation approach, this paper evaluates their differences and usability with actual case studies. Both programs are studied by evaluating the energy efficiency of a laboratory pumping system and of an industrial pumping system in a Finnish paper mill. According to comparison to the laboratory tests, both tools seem to give indicative results about the system energy consumption. However, it should be noted that real industrial pumping systems are often quite complex, so tools by themselves are not usually sufficient for design of entire system, but they are meant to assist in evaluation of achievable improvements in the system energy efficiency.

Introduction

Centrifugal pumps are one of the major energy consuming end-use devices in industrial and municipal sectors all over the world. For example, according to [1] pumping systems account for over one-fifth of the motor electricity consumption in the industrial sector in European Union. Recent studies have shown that there is still plenty of unrealized saving potential in the energy consumption of industrial pumping systems. The energy efficiency could be often significantly improved by using correctly chosen and sized devices, and by applying variable-speed operation instead of inefficient traditional flow control methods. Since lifetime of a pumping system is usually considered to be from 15 to 20 years, energy and operation costs often cover the major share of the life-cycle costs, even though the purchase and installation costs of devices are dominating at the beginning [2]. Therefore the investments that improve pumping system efficiency are not only viable from the energy saving aspect, but also often financially profitable. Two different software tools made to evaluate the possibilities in improvement of pumping system energy efficiency are discussed in this paper.

First tool introduced in this paper is the Matlab-based Pumping System Optimization Tool (PSOT), which optimizes the energy conversion efficiency of the pumping system by choosing the best combination of devices (pump, motor and frequency converter) on the basis of the given load profile. Similar tools, such as US DOE's Pumping System Assessment Tool, have been existed for a long time, but PSOT has several advantages compared to them. Unlike many traditional component selection tools, which usually concentrate only in single device at a time and use only few operation points in selection, PSOT takes into consideration the combined energy efficiency of all system components and uses all given process operation points in the optimization, making optimization process faster and easier. If static head and friction coefficient of a system are known, PSOT can also take into account the change of the flow control method from current one to the variable-speed control. The main window of PSOT is shown in Fig. 1.

Name: procesMidlle
Process points: 428
Total duration: 2140 min
Static head: 0 k: 0

☑ Run pump optimization
☑ Run motor optimization
☑ Run freq. conv. optimization
☑ Calculate LCC

Used efficiency map: Optimal flux
nlimit 1.1
plimit 0.5

Model: sulzer APP43-300 (K14089)
Average mech. power: 177.58 kW

Model: ABB M4BP-315LKC
Nominal power: 250.00 kW

Model: ABB
Nominal current: 430.00 A

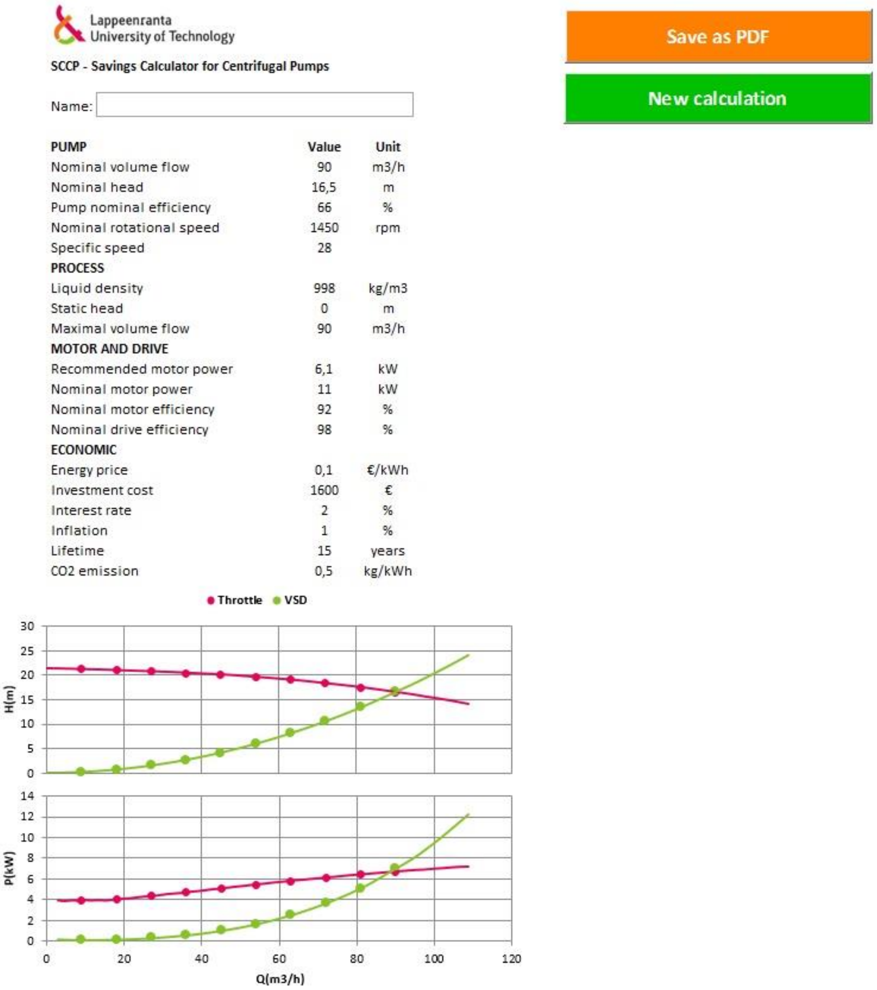
🟥	Inv. costs:	168949	€
🟧	Oper. costs:	172992	€
🟩	Maint. costs:	27487	€
	Total costs:	369428	€

Energy consumption: 6734 kWh/cycle
377620 kWh/a
Average input power: 188.81 kW
Average total Es: 0.11 kWh/m3

Hours / year: 2000
Years in use: 10
Interest rate (%): 5
Annual inflation (%): 3
Electricity price (eur/kWh): 0.05
Motor price (eur/kW): 300
Pump price (eur/kW): 300
Maintenance cost (eur/a): 3000

Fig. 1. Pumping System Optimization Tool's main window.

Another tool introduced in this paper is the Excel-based Savings Calculator for Centrifugal Pumps (SCCP), which is used to assess the savings available by the change of the flow control method. SCCP calculates the achievable savings, when the pumping system components remain the same, but existing throttle control is substituted by variable-speed control. With variable-speed operation, unnecessary production of pressure can be avoided, so the same flow rate can be produced with less power than with throttle control. Because of its simplicity and small number of input parameters, SCCP is an easy tool to start with when assessing the possible improvements in energy efficiency of a pumping system. The detailed calculation results page of SCCP is shown in Fig. 2.



SCCP - Savings Calculator for Centrifugal Pumps

Name:

PUMP	Value	Unit
Nominal volume flow	90	m3/h
Nominal head	16,5	m
Pump nominal efficiency	66	%
Nominal rotational speed	1450	rpm
Specific speed	28	
PROCESS		
Liquid density	998	kg/m3
Static head	0	m
Maximal volume flow	90	m3/h
MOTOR AND DRIVE		
Recommended motor power	6,1	kW
Nominal motor power	11	kW
Nominal motor efficiency	92	%
Nominal drive efficiency	98	%
ECONOMIC		
Energy price	0,1	€/kWh
Investment cost	1600	€
Interest rate	2	%
Inflation	1	%
Lifetime	15	years
CO2 emission	0,5	kg/kWh

Fig. 2. Part of SCCP's detailed calculation results window.

SCCP and PSOT are partially based on the same modeling principles of the pumping system devices, but they also differ significantly on some parts. In this paper, the general principles of the pumping system modeling in both software tools are introduced and their usability is evaluated with laboratory tests and industrial scale case study.

Pumping System Optimization Tool

Unlike traditional component selection tools, which concentrate only in one component of a pumping system at a time, Pumping System Optimization Tool selects the best combination of pump, motor and frequency converter for the given process. With this kind of approach, the entire selection of the pumping system setup can be done by only one software and the total energy conversion efficiency of the process can be optimized. PSOT also calculates the lifecycle costs for the optimized system and shows how it is distributed in investment, operating and maintenance costs.

Pumping System Optimization Tool does the optimization in four individual parts as shown in Fig. 3: 1) the pump, 2) the motor, 3) the frequency converter and 4) the calculation of life-cycle costs (LCC). PSOT has database for each system component type (pump, motor and frequency converter), which are based on information given by manufacturer. This can improve PSOT's accuracy, since performance characteristics of particular device can be applied. User can also add own devices to the database, if it is not readily found from it. The best components are then selected on the basis of these databases. The optimization starts from selection of the most energy efficient pump *p* on the basis of the given load time profile. The best motor *m* can be then selected on the basis of required shaft power from the pump in each operation point. A suitable frequency converter *c* is then selected to meet the motor's requirements. When the optimized pumping system setup is found, the energy consumption and LCC with the given load time profile can be calculated. The calculation principles applied in PSOT are described in the following sections.

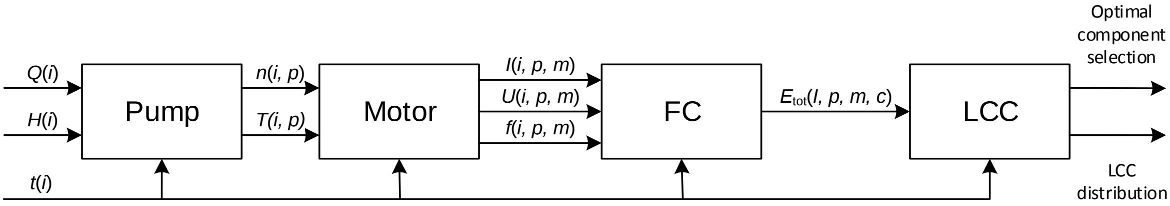


Fig. 3. Simplified block diagram of Pumping System Optimization Tool. The index *i* denotes the *i*th operation point of the given process. The system components are subscribed as follows; *p* is the *p*th pump, *m* is the *m*th motor and *c* is the *c*th frequency converter in the database.

Pump

The first pumping system component to be selected is a pump, which is selected on the basis of given hydraulic operation points. Operation points are given by pairs of flow rate Q and head H as a function of time. PSOT chooses the best pump for the given load profile from the pump database, which in practice contains digitized pump characteristic curves as text files. Characteristic curves describe the pump head H and power P as a function of flow rate Q and they are given for the nominal rotational speed of the pump. The pump selection is based on calculating the energy consumption of all options and by choosing the best alternative of them for the given application. To be able to describe all operation points, curves are converted to cover the operation points outside the curve by the well-known affinity laws described by equations

$$Q = \left(\frac{n}{n_0}\right) Q_0, \tag{1}$$

$$H = \left(\frac{n}{n_0}\right)^2 H_0, \tag{2}$$

$$P = \left(\frac{n}{n_0}\right)^3 P_0, \tag{3}$$

where n is rotational speed and the subscript 0 denotes the initial value. The required rotational speed n and power P in given operation points can be then calculated on the basis of these affinity laws, by applying the QP-curve-based estimation method described in [3]. The required torque T from the motor is then calculated by the equation

$$T = \frac{P}{2\pi \frac{n}{60}}. \tag{4}$$

PSOT also provides an option to input static head H_{st} and friction coefficient k. If these system parameters are given, PSOT can take into consideration the change of the flow control method from the one applied in the given process to the variable-speed drive, in which the required flow rate is produced with minimum pressure allowed by the system. With this kind of flow control scheme, all operation points are located in the system curve, which is described by the equation

$$H_{\mathrm{sys}} = H_{\mathrm{st}} + kQ^2, \tag{5}$$

where H_{sys} is the system head. The given process head values are then substituted by the system head values. It should be noted that this is optional and should be used only, if it is possible to substitute the current control method with variable-speed control.

The energy consumption of a pump as well as the total energy consumption of the system can be then calculated on the basis of given load time profile by the equation

$$E = \sum_{i=1}^{l} P_i t_i, \tag{6}$$

where *E* is energy consumption and *t* is a time used in each operation point. Subscript *i* denotes the individual operation points and *l* is the total number of given operation points. The pump with the smallest energy consumption is then selected.

Motor

In motor selection part, the most suitable induction motor for the pump is selected from the similar database as applied to the pump selection. The database includes efficiency maps for the motors, which are created by approximating the equivalent circuit of an induction motor on the basis of motor catalogue information [4]. The efficiency maps are created for both optimal and constant flux control scheme, but without considering the losses caused by non-sinusoidal supply voltage from the frequency converter. These provide indicative information of the flux optimization effect in energy consumption. The efficiency is then determined from the efficiency map on the basis of rotational speed and torque. An example of approximated induction motor efficiency map is shown in Fig. 4.

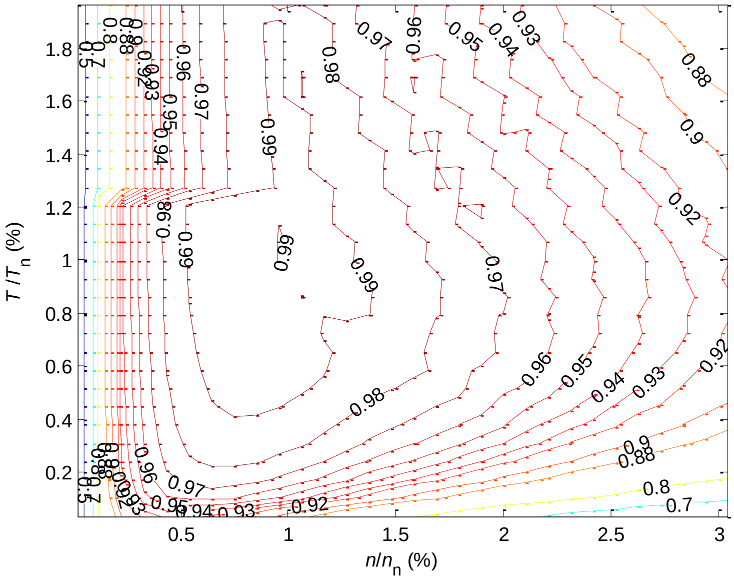


Fig. 4. An example of approximated induction motor efficiency map applied in PSOT with a nominal rotational speed of 1482 rpm and a nominal power of 37 kW. Rotational speed, torque and efficiency in the map are relative to the nominal values.

Frequency converter

The most suitable frequency converter for the given application is selected on the basis of easily available catalogue information. Conventional methods to approximate the frequency converter efficiency may be therefore too complex to use, because they usually require parameters that are difficult to produce from data provided by manufacturers. Instead of using a pre-generated efficiency maps like in the motor section, the power losses P_l in frequency converter are approximated by the equation presented in [5]:

$$P_\mathrm{l} = \left(0.35 + 0.1\frac{f}{f_\mathrm{n}} + 0.55\frac{T}{T_\mathrm{n}}\right) * P_\mathrm{ln}, \tag{7}$$

where *f* is frequency and subscript n denotes the nominal value. Only a rough approximation of frequency converter losses can be attained by using this equation, but while the efficiencies of frequency converters are usually very high, this approximation should be accurate enough to calculate the energy consumption with sufficient accuracy. Frequency converter efficiency can be then defined in each operation point on the basis of the calculated losses.

Life-cycle cost calculation

Life-cycle costs of the optimized pumping system setup are calculated on the basis of the given economic information and calculated energy consumption with the given load profile. The lifecycle costs is distributed in investment, operation and maintenance costs. In operating and maintenance costs, the inflation and interest rate are taken into account by calculating their net present values (NPV).

Savings Calculator for Centrifugal pumps

SCCP is a software tool for a quick analysis of the viability of change of flow control method from throttling to variable-speed operation. Even though variable-speed operation in a pumping system is already quite an old invention, throttle control is still used very widely, even if the energy efficiency of a pumping system could be often remarkably improved by using a variable-speed control. Therefore the main purpose of SCCP is to reliably show that in most cases significant energy and financial savings could be achieved, by relatively small investment in variable-speed drive. SCCP is not only of its kind, but there already exists many similar tools, for example ABB PumpSave and Vacon Save. Compared to them, SCCP requires less input information and has different calculation approach in modelling of pumping system devices. In addition, SCCP also provides an option to input the flow profile of the process with time stamped flow and save detailed PDF report.

SCCP is quite simple tool and requires only a small amount of input information from the user, so it can be easily used even by an uninitiated person, which makes it a good tool for marketing purposes. Due to small amount of input parameters, the accuracy of the tool can significantly vary depending on a case, and therefore it should be used mainly to show the benefits of variable-speed control with reasonable accuracy. Only nameplate information of a pumping system components and process information are required. On the basis of the given information, SCCP calculates achievable energy and financial savings in the system, and also some usable economic quantities. Like in PSOT, the modelling of the pumping system is divided in four different parts: 1) the pump, 2) the motor, 3) the frequency converter and 4) the energy consumption and economics. The simplified block diagram of calculation steps is shown in Fig. 5.

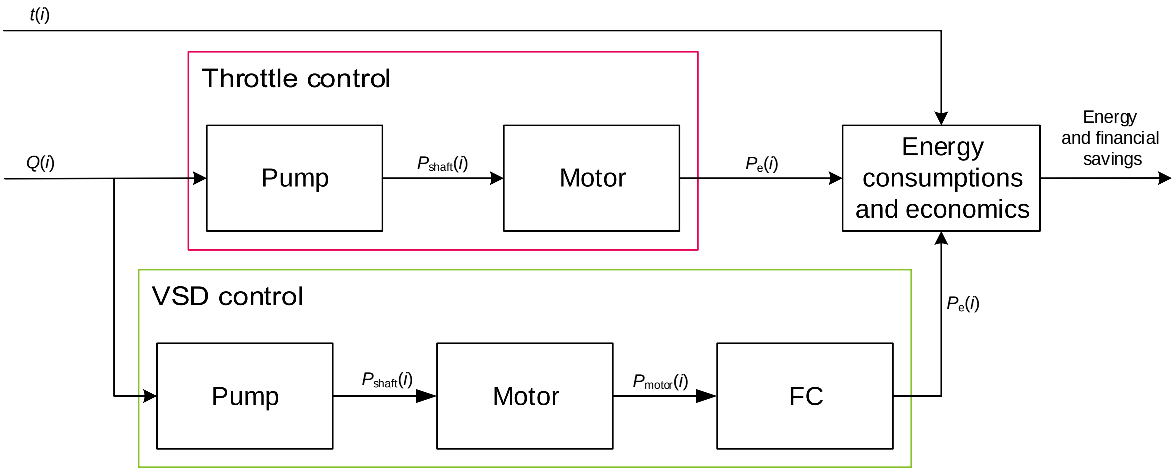


Fig. 5. Simplified block diagram of SCCP. The index *i* denotes the *i*th operation point of the given process.

As Fig. 5 illustrates, SCCP has two calculation branches since it compares two different flow control methods. The models for pumping system devices are different in both branches for some devices. The modelling principles of each devices with both control methods are introduced in next sections.

Pump

The calculation of the saved energy on the basis of the given operation points begins on evaluation of the pump characteristic curves. In contrast to PSOT, SCCP does not apply any kind of database of pump characteristic curves, but it estimates the curves on the basis of given nameplate information. The characteristic curves for pump head and efficiency are created on the basis of pump specific speed n_q, which is a dimensionless quantity that is used to describe the centrifugal pump characteristics regardless of pump size. Specific speed can be defined on the basis of the pump nominal values by the equation

$$n_{\mathrm{q}} = n_{\mathrm{n}} \frac{\sqrt{Q_{\mathrm{n}}}}{{H_{\mathrm{n}}}^{3/4}}, \tag{8}$$

where subscript n denotes the nominal value. The pump characteristic curves can be then estimated on the basis of calculated specific speed. In SCCP, head and efficiency curves are interpolated from the digitized curves relative to pump nominal values, originally published in [6]. These digitized curves are shown in Fig. 6.

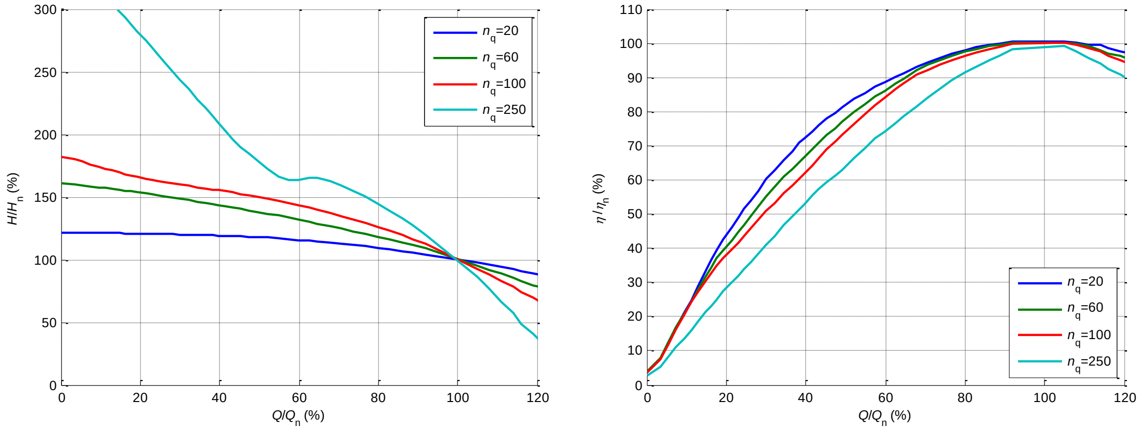


Fig. 6. Relative pump head and efficiency curves used in estimation in SCCP.

While a throttle controlled system can be modelled on the basis of these pump characteristic curves, the modelling of the variable-speed controlled system requires a little more complex approach. With variable-speed operated system, the desired flow rate is assumed to be produced with as small amount of pressure as possible. The minimum amount of head can be described by the system curve, which is defined by (5).

Since a rotational speed is not constant in variable-speed operated system, also the pump efficiency requires a different calculation approach than with throttle controlled system. First, the required rotational speeds in desired operation points are calculated on the basis of second degree polynomial fitting created from the interpolated pump head curve. The rotational speed can be calculated on the basis of this fitting, which is described by the equation

$$H = AQ^2 + BQ\left(\frac{n}{n_{\mathrm{o}}}\right) + C\left(\frac{n}{n_{\mathrm{o}}}\right)^2. \tag{9}$$

To solve the required rotational speed in certain operation point, the fitting is converted by varying the rotational speed so that the fitted curve intersects the system head curve defined by equation (5) at the operation point’s flow rate value, in other words when $H = H_{\mathrm{sys}}$.

When rotational speed is known, the pump efficiency can be calculated. There exists multiple different models to approximate the efficiency of a variable-speed operated pump, but in SCCP, the equation given in [7] is used:

$$\eta_{\text{pump}} = 1 - \left(1 - \eta_{\text{n,pump}}\right)\left(\frac{n_{\text{n}}}{n}\right)^{0.1}, \tag{10}$$

where η is the efficiency and n denotes the nominal value. With both control methods, a required shaft power P_{shaft} in given operation points can be then calculated by the equation

$$P_{\text{shaft}} = \frac{\rho Q H g}{\eta_{\text{pump}}}, \tag{11}$$

where ρ is the liquid density and g is the acceleration due to gravity (~9.81 m/s^2). Now when the rotational speed and shaft power in each operation point are known, the required torque can be calculated by the equation (4).

Motor

The motor efficiency in SCCP is estimated by the same kind of motor efficiency map than in PSOT. While PSOT applies the comprehensive database for motor efficiency maps, SCCP uses only one map for the simplicity. The used efficiency map in SCCP is for ABB M4BP 225SMA 4-pole 37 kW motor, which was chosen to describe the average induction motor driving a pump on the basis of [8].

Frequency converter

Frequency converter is modeled in SCCP with similar equation than in PSOT. Only difference from the equation (7) is that the relative frequency is substituted by relative rotational speed. This substitution is valid, when the slip of an induction motor is assumed to remain constant. Even if slip varies, it shouldn't have significant effect on the power consumption. When motor and FC efficiencies are known, required electric power for the system can be calculated. In the calculation of energy consumption of throttle controlled system, frequency converter efficiency is ignored.

Energy consumption and economics

On the basis of given load profile and calculated electric power consumptions, the annual energy consumptions with both throttle and variable-speed controlled systems can be calculated by the equation (6). When the economic conditions are provided by the user, also the net present value of the achievable savings and some economic quantities, such as payback period and internal rate of return can be calculated.

In calculation of the annual energy consumption, the given load profile is assumed to be repeated for an entire year. The annual consumptions are calculated separately on both of the control methods. On the basis of the given economic conditions, annual and lifetime financial savings can also be calculated. The lifetime savings are given in net present value of savings, which can be calculated by the equation

$$S_{\text{lifetime}} = \sum\nolimits_{k=1}^{l} \left(\frac{S_{\text{annual}}}{(1+i)^k}\right) - C_{\text{investment}}, \tag{12}$$

where *S* denotes the savings, *i* is the interest rate, *l* is the lifetime of the pumping system and *C* is the costs. Another good way to evaluate a profitability of an investment is calculating internal rate of return (IRR), which is the discount rate that makes the net present value of all savings achieved from investment equal to zero. In other words, IRR can be considered as the attainable rate of return of investment, but without concerning the environmental factors such as inflation and interest rate. IRR has to be solved by iterating it from the equation

$$\sum\nolimits_{k=1}^{l} \left(\frac{S_{\text{annual}}}{(1+\text{IRR})^k}\right) - C_{\text{investment}} = 0. \tag{13}$$

As a result of reduced energy consumption, also the level of emissions produced in energy generation is decreased. Therefore SCCP also gives the achievable reduction in CO_2 emissions by the change of flow control method.

Case studies

Both software tools are tested by evaluating the energy saving potential in two different cases. In the first case, accuracy of software tools is studied in both throttle and VSD controlled cases through laboratory tests. In the second case, PSOT is tested by assessing the savings available by optimizing the pumping system setup in a Finnish paper mill.

Laboratory measurements

The accuracy of both software tools is evaluated by comparing them to the laboratory measurements done in LUT pump laboratory. The main purpose of laboratory tests was to ensure the accuracy of software tools in calculation of energy consumptions in throttle and variable-speed controlled closed and open loop systems. The laboratory setup consists of Sulzer APP22-80 centrifugal pump with 255 mm open impeller, ABB M3BP160M4 11 kW induction motor and ABB ACS880 frequency converter. The piping of the laboratory system includes multiple sensors for pressure, flow rate and temperature. In addition, the pump shaft is equipped with torque and rotational speed sensors and the consumed electric power is also measured.

The measurements were carried out by using the so called Heating-Ventilating-and-Air-Conditioning (HVAC) load time profile, which is used as a standardized load time profile in calculation of Energy Efficiency Index (EEI) for circulators or closed loop variable flow systems, and it has already been established in EN-Standardization and EU-Regulation for circulators [9]. The standardized load time profile is shown in Tab. 1.

Tab. 1. The standardized load time profile for closed loop variable flow systems used in laboratory measurements.

Operation point	Flow rate [%]	Time [%]
L_1	100	6
L_2	75	15
L_3	50	35
L_4	25	44

As can be seen in Tab. 1, the load time profile has a high emphasis on part-load operation points. It is also designed for closed loop applications, so it might not describe very well usual industrial applications. It is still used due to standardization and to provide wider operation range for better assessment of accuracy of tools, since modeling of the system is often more difficult at part-load operation.

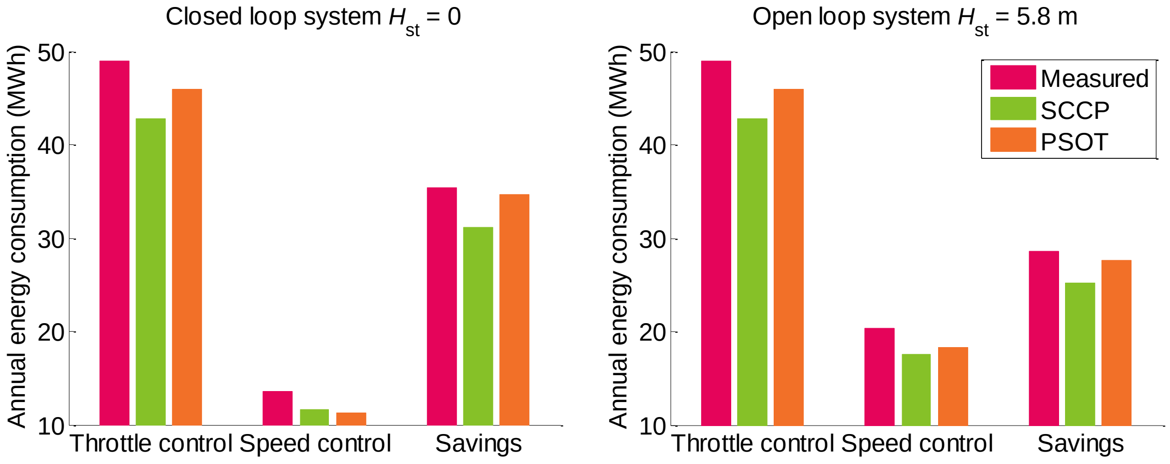
The standardized load time profile test runs are executed for closed and open loop systems, with both throttle and variable-speed controls. Static head H_{st} in closed loop system is zero and in open loop system 5.8 meters. In throttle controlled measurements, flow rate is regulated only by throttling a valve, while pump is run at the constant rotational speed of 1450 rpm. In calculation of EEI, in which the standardized load time profile is applied, the variable-speed operation is assumed to be executed with standardized pressure control curve [9]. To execute this kind of pressure control curve, the system needs to be controlled by both throttle and variable-speed drive. However, PSOT and SCCP are assuming that the desired flow rate is produced with the minimal amount of pressure by using only variable-speed drive, so the standardized pressure control curve cannot be applied in the evaluation of the accuracies of software tools. For this reason, in variable-speed controlled measurements the pump is controlled only by adjusting rotational speed of the motor, while remaining the same valve position.

To evaluate the accuracy of SCCP and PSOT, the results of the laboratory measurements are compared to the results calculated by the software tools. PSOT requires flow rate and head as a function of time from the throttle controlled measurements as an input. In calculation of energy consumption of variable-speed controlled systems, also static head H_{st} and friction coefficient k are given. The pump, motor and frequency converter used in laboratory setup are selected from the component databases of PSOT to be used as the only possible options in optimization. While SCCP does not have any kind of databases for system components like PSOT, the nameplate information of pumping system devices shown in Tab. 2 is required as an input.

Tab. 2. Nameplate and system information of the laboratory setup used as input for SCCP

Pumping system information	
Nominal flow rate	90 m^3/h
Nominal head	16.5 m
Pump efficiency	66 %
Liquid density	998 kg/m^3
Static head	0 m and 5.8 m
Rotational speed	1450 rpm
Nominal motor power	11 kW
Nominal motor efficiency	92 %
Nominal drive efficiency	98 %

To make the results given by SCCP and PSOT comparable to the laboratory measurements, the annual energy consumption of the laboratory setup has to be calculated. This is done by assuming the pump is driven with same load profile 8760 hours in year. The measured and calculated annual energy consumptions and achievable energy savings are shown in Fig. 7.



(a) (b)

Fig. 7. Measured and calculated annual electric energy consumptions and energy savings in closed loop system (a) and in open loop (H_{st} = 5.8 m) system (b).

As Fig. 7 illustrates, the actual measured electric energy consumptions are higher than estimates of SCCP and PSOT in both throttle and speed controlled closed and open loop cases. Energy consumption with throttle control is basically same in both open and closed loop systems, since static head has no effect on the head produced by pump. There SCCP and PSOT estimates of annual electric energy consumption are 12.7 % and 6.4 % lower, respectively, than measured consumption in throttle controlled laboratory system. The achievable energy savings by variable-speed control in closed loop system are illustrated in Fig. 7 (a). There SCCP gives 14.5 % lower and PSOT 17.1 % lower electric energy consumption compared to the measured variable speed controlled system electric energy consumption. In open loop system, static head increases the energy consumption of variable speed controlled system as shown in Fig. 7 (b), due to increased head in part-load operation. There estimates of SCCP and PSOT are 13.8 % and 10.4 % lower, respectively, than measured electric energy consumption.

As the estimated energy consumptions are remarkably lower than measured ones, the actual achievable savings will be even greater than predicted by SCCP and PSOT. This means that the installing of a frequency converter would be even more profitable than can be expected according to software tools. One reason for difference in the results may be the fact that in laboratory setup the induction motor is run by frequency converter also in throttle controlled system, in which frequency converter normally wouldn't exist. The use of frequency converter in throttle controlled system causes some additional power losses. However, according to measurements, the frequency converter efficiency in entire range of flow rates is about 98 % on average, so the additional energy consumption in throttle controlled system cannot be totally explained by it. Frequency converter can also decrease motor efficiency due to non-sinusoidal supply voltage.

SCCP approximates the relative savings of 72.9 % for closed loop system and 58.9 % for open loop system, when using throttle control is substituted by variable-speed control. Correspondingly PSOT gives 75.5 % savings for closed loop system and 60.2 % for open loop system. When calculating the actual savings from the measured values, the result is 72.3 % for closed loop system and 58.4 % for open loop system. The very high savings are mainly caused by profile's high emphasis on part-load operation.

The accuracy of pump modelling in SCCP has been already studied in [10] and the modelled pump characteristic curves corresponded to the measured and manufacturer's curves quite well despite the small number of input parameters. In order to get more information about the calculation accuracy of SCCP, the measurements presented in this paper were also used to study the accuracy of SCCP's estimates for electric power consumption and efficiencies of all pumping system components in presented measured systems. Measured and estimated electric power consumptions as a function of flow rate are shown in Fig. 8.

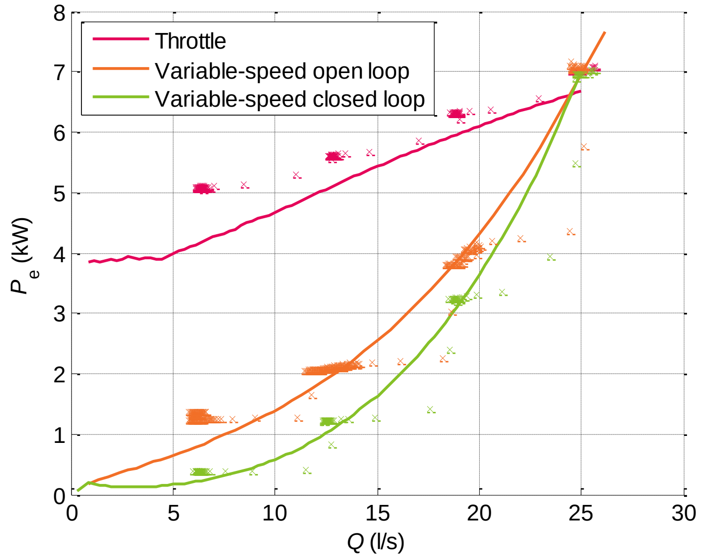
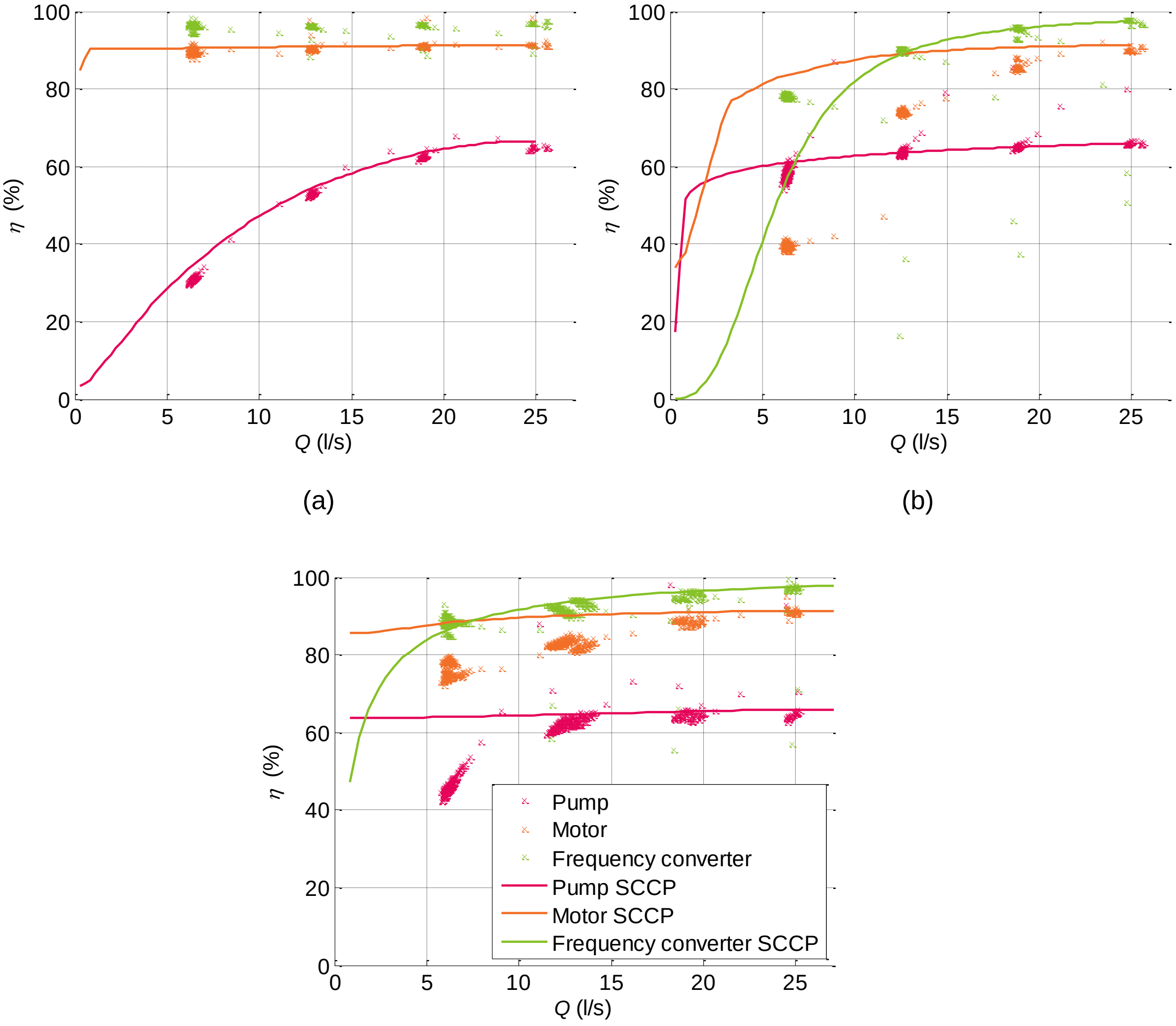


Fig. 8. Measured and SCCP's estimations of electric power consumption as a function of flow rate. Measured values are illustrated by individual points and SCCP estimates are illustrated by lines.

As can be seen in Fig. 8, SCCP estimates electric power consumption estimates are quite accurate for variable-speed operated systems, but have significant error with throttle controlled system, which may be caused by same the reasons mentioned for deviations between electric energy consumption measurements and estimates. To investigate the effect of accuracy of efficiency models for different devices, the measured and calculated efficiency values as a function of flow rate are compared in Fig. 9.



(a)

(b)

(c)

Fig. 9. Measured and SCCP's estimations of efficiencies for pumping system devices in throttle controlled system (a), variable-speed controlled closed loop system (b) and variable-speed controlled open loop (H_{st} = 5.8 m) system (c).

As can be seen from Fig. 9 (a), efficiency models in throttle controlled system are very accurate according to the laboratory measurements. Since the laboratory setup is driven by frequency converter, also measured frequency converter efficiency is shown in the figure, even though it does not usually exist in throttle controlled system. Efficiencies of devices in variable-speed controlled closed loop system are illustrated in Fig. 9 (b). As can be seen, efficiency model for pump is nearly perfectly accurate, but with motor and VSD efficiency estimates there is much more deviation from the measured values. VSD efficiency model seems to be accurate, when flow rate is greater than 50% of the nominal value, but with lower flow rates the estimate for efficiency is too low. Motor efficiency model gives too optimistic values in the full range of flow rates. However, in variable-speed controlled open loop system, the accuracy of pump efficiency decreases especially with low flow rates, while motor and frequency converter efficiency estimates improve significantly compared to the closed loop case, as shown in Fig. 9 (c).

Finnish paper mill

The usability of PSOT in actual industrial scale case was tested by evaluating the energy savings potential in a Finnish paper mill, on the basis of data gathered from the process over a 100 days with a 5 minute sampling interval. The pumping system at the paper mill includes Sulzer APP54-400 centrifugal pump with 990 rpm nominal speed and an open impeller, ABB 400 kW 991 rpm induction motor and ABB ACS800 frequency converter with 521 A nominal current. The pumped mass is a 1.5% density pulp suspension, so the pump has to have an open impeller, which has been taken into account in the pump selection. ABB Low Voltage Process Performance motors in IE2 efficiency class were only motors used in motor selection part, because the currently installed motor has the same efficiency classification. The average power consumption of the system during the measurements is approximately 226 kW and the total energy consumption during 2400 hour period is approximately 540 MWh. The system is controlled by both throttle and variable-speed drive to remain the constant pressure, so pure variable-speed control cannot be applied in this process. For this reason, SCCP is also not suitable for evaluation of energy savings in this case.

PSOT proposes for the optimal setup for the given application Sulzer APP62-400 pump with 745 rpm nominal speed and ABB 315 kW 743 rpm induction motor. The already installed ABB ACS800 frequency converter was identified to be the most suitable one for the process. According to PSOT, by using the optimized component setup, the power consumption would be reduced by almost 20 % to 186 kW and energy consumption would be 445 MWh with the given load profile. The annual energy savings with assumed 7000 h annual operating time would be 280 MWh, which corresponds to 28 000 € savings with energy price of 100 €/MWh. With assumed 5 % interest rate and 3 % inflation, the lifetime savings in 10 years would be even 300 000 €. This would mean reasonable payback period from two to three years for new pump and motor. More detailed information about the case is available in [4].

Conclusion

Pumping applications are one of the most energy consuming systems in both industry and municipal sectors all over the world. Since the major share of the life cycle costs of pumping system comes often from the energy consumption, the selection of the pumping system components and flow control method is essential from the energy and financial saving aspects. Two software tools to evaluate the possible improvements in energy efficiency of pumping systems, Pumping System Optimization Tool (PSOT) and Savings Calculator for Centrifugal Pumps (SCCP), were introduced in this paper.

There exists several selection tools for pumping system components, which are used to select the best device for the process. One problem with the existing selection tools is that they usually concentrate in a single device at a time and use only few operation points of the process in calculation. In contrast to them, Matlab-based PSOT selects the most optimal combination of all pumping system components (pump, motor and frequency converter) and takes into consideration all given operation points. With this kind of approach, the entire pumping system setup can be optimized at one time. Another tool introduced in this paper is SCCP, which takes into consideration only the flow control method of the pumping system. Significant share of pumping systems is still nowadays controlled by inefficient throttle control, even if it would be often financially viable to replace it by more energy efficient variable-speed control. SCCP is a simple Excel-based tool to evaluate the achievable energy and financial savings, when the throttle control is substituted by the variable-speed control. The modelling principles of both software tools and their differences are introduced in this paper.

The accuracy and usability of both software tools was explored in this paper through two case studies. In first case study, the accuracy of software tools was evaluated by comparing their calculations of energy consumptions to the laboratory measurements, in both throttle and variable-speed controlled case. The accuracies of efficiency models for different devices in SCCP were also evaluated through the laboratory tests. According to the measurements, both PSOT and SCCP give indicative results about the profitability of the replacement of throttle control with variable-speed control, with the achievable savings of over 70 %. The usability of PSOT was also studied through industrial scale case. PSOT proposed optimized pumping system setup for a Finnish paper mill that would reduce the average consumption by almost 20 %. These cases confirm that there is still need to develop this kind of tools to achieve improvements in energy efficiency of pumping systems. Already existing tools can provide indicative information about the profitability of replacements of devices or change of the control method in pumping systems, and therefore encourage to make investments to achieve better energy efficiency.

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