

General Methodologies of Determining the Energy-Efficiency-Index of Pump Units in the Frame of the Extended Product Approach

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Abstract

Quantifying the energy efficiency of pump units across markets is a tough task: These units mostly consist of rotodynamic pumps driven by motor systems either without or with variable-speed drives, the latter being called power drive systems (PDS). To evaluate the energy efficiency of such arbitrary pump units in the frame of the Extended Product Approach (EPA), the Energy-Efficiency-Index (EEI) is introduced as a normalized weighted average of electrical power input of a pump unit operated at different duty points of a standardized load-time profile. If the unit is equipped with a variable-speed drive, the duty points also have to be adjusted according to a standardized pressure control curve. The EEI is therefore a measure of energy efficiency and represents simultaneously the quality of the Extended Product “pump unit” and the characters of the standardized load-time profile and the standardized pressure control curve. The two general methodologies to determine the EEI presented in this paper are valid independently of a particular standardized load-time profile or pressure control curve.

Besides determining the EEI experimentally, an alternative methodology is necessary to establish a market-wide EEI determination with reasonable effort for manufacturers, system integrators and customers. The alternative approach described in this paper is capable of modeling the part load behavior of the pump unit’s components with sufficient accuracy. To achieve this, the methodology rests upon physically based semi-analytic models of the components of the pump unit. The models are adapted to the corresponding real components by means of a small amount of well-defined data. The methodology is reported in its general form in this paper, treating the underlying semi-analytic models themselves as black-boxes. The approach is developed and experimentally validated within the scope of a EUROPUMP project carried out at Technische Universitaet Darmstadt, Germany.

Introduction

The political goal to increase the sustainability of the energy production and utilization inside the European Union, especially to reduce the emission of CO₂, has led to the ecodesign directives 2005/32/EC [1] and 2009/125/EC [2]. These were intended to increase the energy efficiency of energy using and energy related products. Starting from preparatory studies and accompanied by a consecutive exchange of information with the association of European pump manufacturers (EUROPUMP), the European Commission has passed two pump-specific regulations on a legislative level which came into force on January 1st, 2013.

The first of these regulations [3] applies to circulator pumps for heating and hot water circuits. The second regulation [4] applies to rotodynamic clean water pumps of specified types within a scope of nominal data (c.f. [5]). These pumps are classified in respect to energy efficiency by a so called Minimum-Efficiency-Index (MEI), a classification system of lower limits for the pump’s efficiency at three specified flow rates: one at 75 % part load, one at 110 % over load and one at best efficiency point (BEP). The classification according to the MEI is standardized in a coming EN standard [6] while the corresponding legislative regulation [4] specifies the minimum values of MEI that have to be fulfilled to allow the product to be placed on the market. Comparable regulations exist in the field of asynchronous motors: The system of IE classes that was adopted in 2008 [7], classifies asynchronous motors with respect to their efficiency at nominal load condition.

Both the regulation affecting the water pump market [4] and the system of IE classes [7] affecting the market of asynchronous motors can be summarized under the keyword “Product Approach”. The energy savings of measures in the frame of a Product Approach result from forced increases of the product efficiency. This way of reducing the energy consumption requires high effort by the manufacturers as the design of the product in relation to its efficiency and the manufacturing

technologies etc. have to be improved. Furthermore, the question whether the product is applied in an energy efficient way is blinded out completely by a Product Approach.

These reasons have motivated to extend the Product Approach to a concept called Extended Product Approach (EPA) that includes both the efficiency and the application of a product. In respect to pumps, the Extended Products consist of a pump and a motor system. The latter is an electric motor with or without a Variable Speed Drive (VSD).

The Extended Product Approach has already been successfully introduced in the field of circulator pumps in the European Union by regulation [3] mentioned above, where the determination of a value called EEI (Energy-Efficiency-Index) is mandatory for every circulator pump since January, 2013.

To also apply the EPA on rotodynamic clean water pumps and to assess them by an adequately defined EEI-value is problematic since there are serious differences between typical circulator and clean water pumps that need to be addressed. Circulator pumps are generally sold as fully integrated products where all the product's components (rotodynamic pump and electric motor without or with variable-speed drive) are technically aligned to each other by one manufacturer and the customer is not intended to combine these on his own. Therefore the determination of EEI is clearly allocated to one accountable institution.

In contrast to that, the combination of individual components (which also might be delivered by different manufacturers) to complete pump units by a system integrator company is an important case in the field of clean water pumps and therefore cannot be neglected. Neither the responsibility nor the methodology to determine the EEI of such Extended Products in the field of clean water pump units is straightforward. A market-wide experimental determination of the EEI would additionally cause high effort to manufacturers and/or system integrators. An alternative determination methodology is therefore desirable or – even more – urgently necessary to enable the energy efficiency qualification of rotodynamic clean water pumps according to the EPA across markets.

This paper describes an experimental as well as a so-called semi-analytical methodology to determine the EEI for clean water pump units in the frame of the EPA. The main focus in this paper will be on the semi-analytic methodology.

The Extended Product Approach

The Extended Product Approach (EPA) for rotodynamic clean water pump units (c.f. Fig. 1) focuses presently on pump units of different types and sizes that are widely applied in the field of clean water pumping. The pumps are driven by asynchronous motors without or with Variable-Speed Drives (VSD), the latter being called Power Drive Systems (PDS). In the sense of European legislation and standardization, these fixed-speed and variable-speed pump units are “Extended Products”.

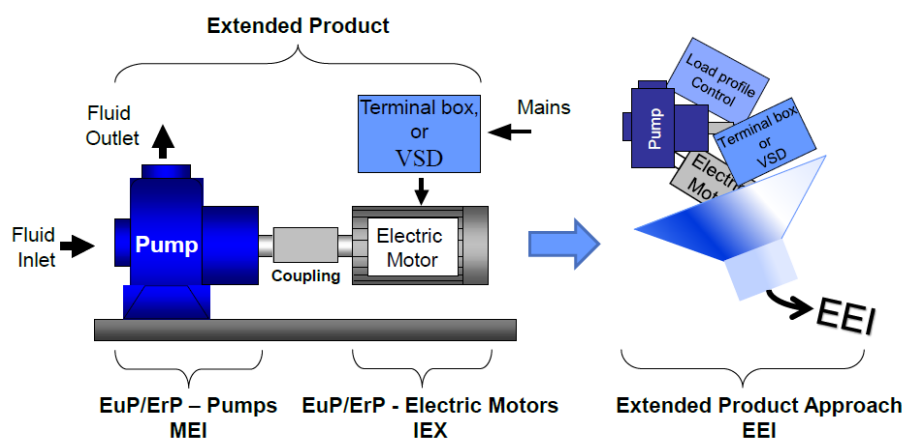


Fig. 1: The Concept of the Extended Product Approach

Adapted from [8] with kind permission of the authors

Basic feature of the EPA is the consideration of an energy efficient application of the Extended Product in addition to the product efficiency alone as it is the case in a Product Approach. To reach this, a load-time profile and a pressure control curve (c.f. below) need to be incorporated in the methodology. Result of the EPA is the EEI, a value representing both the efficiencies of the Extended Product's components and its suitability in terms of energy efficiency for the load-time profile and pressure control curve the determination of the EEI is based on (cf. Fig. 1).

Ideally, a load-time profile would represent the particular application a pump unit needs to be chosen for in the best way possible, but two serious problems prevent the realization of this: Firstly, the customer respectively system integrator would need to apply the EPA and determine an EEI for every available pump unit in the market on his own in order to find the most energy efficient one for any particular application. Secondly, a load-time profile representing sufficiently well the particular application is costly to determine and therefore in most cases not available.

To overcome these problems, to enable a market-wide determination of EEI values and to maintain comparability between different pump units despite of the different applications they are used in, standardized load-time profiles are established for different types of applications. The intention of these standardized load-time profiles is not to represent particular applications in the best way possible. In fact, they shall constitute representative applications – that are not too far from typical load-time profiles in the particular types of application – only for the purpose of applying the EPA and thus determining the EEI.

The introduction of these standardized load-time profiles as common bases enables a sufficiently accurate prediction of the relative differences in terms of energy efficiency between different pump units for various types of applications: The better the EEI of a pump unit based on the standardized load profile for a particular type of application is, the more energy efficient this pump unit will most likely perform in the real application of the same type, too. Thus a further aspect of competition is introduced to the market via the EPA.

It should be pointed out that the standardized load-time profiles exclude any idle time of the pump unit: Only the performance of the running extended product is considered. This is reasonable, because the interaction of the extended product with the application or system it is used in (e.g. on/off-switching controlled by level switches) is not intended to be included in the qualification in terms of energy efficiency in the sense of the EPA. Future concepts e.g. in the sense of system approaches might be able to include the interaction of extended products with the applications or systems they are used in into one measure of energy efficiency qualification. In contrast to that, the EPA is intended to qualify pump units as extended products that could be taken out of a box and installed into an application or system afterwards.

At the time this paper was written, different standardized load-time profiles representing different types of applications were considered by the EUROPUMP working group developing the EPA. For detailed information on the status of these discussions as well as further information on the concept of the EPA in general, it is recommended to refer to [8]. In the present paper, the so called Heating-Ventilating-and-Air-Conditioning (HVAC) load-time profile is generalized for closed loop applications of clean water pumps. It is used in this paper as standardized load-time profile for demonstration and explanation of the methodologies to determine the EEI in the frame of the EPA (cf. Fig. 2). It should be noted that this restriction clearly affects the numerical values used to illustrate the methodical procedures in the course of the paper. Nevertheless, the general methodologies to determine the EEI presented in this paper are valid independently of a particular load-time profile.

The load-time profile for closed loop applications is characterized by the rated flow rates $Q_i/Q_{100\%}$ where the subscript 100% denotes the nominal operating point of the pump (corresponding to the pump's best efficiency point at its nominal rotational speed $n_{100\%}$) and time weights $\Delta t_i/t_{tot}$ listed in Tab. 1. The time weights represent which fraction Δt_i of the total operating time t_{tot} (excluding the time the unit is switched off) the pump unit is operated at the individual value of flow rate. The load-time profile as it is listed in Tab. 1 has been determined by [9] and is internationally accepted as being representative for the very important application field of building technology. It should be noted that according to Tab. 1 a load-time profile is only characterized by values of flow rate and time weight for each duty point and not by values of the pump head H .

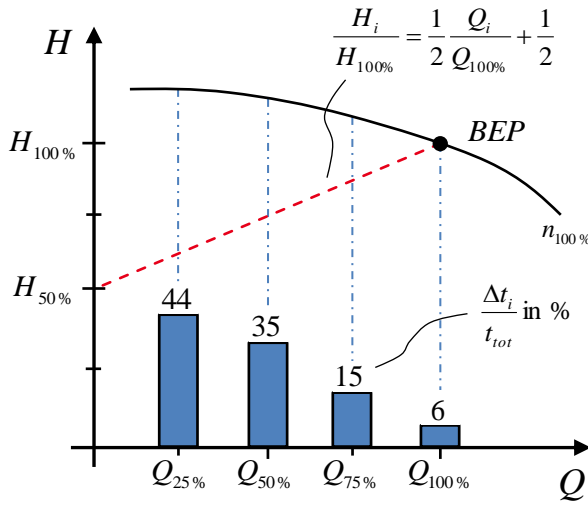


Fig. 2: Standardized load-time profile and pressure control curve for closed loop applications

Tab. 1: Standardized load-time profile for closed loop applications

Rated Flow Rate $Q_i/Q_{100\%}$	Time Weight $\Delta t_i/t_{tot}$
1	6 %
0.75	15 %
0.5	35 %
0.25	44 %

In case of fixed-speed pumps (pump units driven by asynchronous motors without VSD) the relevant duty points for determining the EEI are straightforward: The rotational speed of the asynchronous motors of these pump units fed directly by the electric grid is determined by the constant frequency of the electric grid f_1 according to Eq. (1)

$$n = n_{synch} (1 - s) \quad (1)$$

where $n_{synch} = f_1/N_p$ is the synchronous speed, N_p is the number of pole pairs of the asynchronous motor and $s = (n_{synch} - n)/n_{synch}$ is the slip. As the slip only slightly varies with the duty point and generally is much smaller than unity, the rotational speed of fixed-speed pumps can be assumed as being approximately constant $n \approx n_{100\%}$. In order to fix the nominal rotational speed $n_{100\%}$ that strongly influences the hydraulic performance of the rotodynamic pump for the purpose of EEI determination and to maintain comparability between different products, the nominal rotational speeds are defined in the frame of the EPA as

$$\begin{aligned} n_{100\%} &= 2900 \text{ rpm in case of units equipped with 2-pole motors and} \\ n_{100\%} &= 1450 \text{ rpm in case of units equipped with 4-pole motors.} \end{aligned} \quad (2)$$

These values of the nominal rotational speeds have grown historically in European legislation and standardization: The EUROPUMP working group responsible for the development of the EPA defined

the nominal rotational speeds of pumps in the frame of the EPA according to Eq. (2) to be in line with the MEI classification system for water pumps. For this classification system, nominal rotational pump speeds had to be defined to establish comparability between different pumps as well (c.f. [6]).

In contrast to fixed-speed pump units, the relevant duty points for determining the EEI of a variable-speed pump unit (pump unit driven by asynchronous motor with VSD) are not straightforward. Due to the ability of varying the rotational speed by varying the motor stator frequency e.g. via a frequency converter, these units are able to be operated at duty points distributed over a wide range of the Q - H -plane (c.f. Fig. 2).

In many applications where highly varying flow rates are demanded as is the case for the closed loop load-time profile used as example in this paper (c.f. Fig. 2 and Tab. 1) the smaller values of flow rate could easily be delivered by the pump with decreased pump head, too. To exploit this potential of saving energy and reduce the pump head compared to the corresponding value on the pump characteristic at $n_{100\%}$ the rotational speed needs to be reduced at reduced flow rate.

Generally, manufacturers and system integrators use their own control strategy following which the rotational speed is reduced according to decreasing flow rates. Furthermore, these control strategies can often easily be changed by changing the software settings of the VSD (e.g. frequency converter). To reach comparability of EEI values of variable-speed pump units across markets in spite of such individual control strategies, standardized pressure control curves are established for various types of applications.

As is the case for the standardized load-time profiles mentioned above, the purpose of the standardized pressure control curves is not to represent individual applications in the best way possible, but to provide representative control curves as a common base. These standardized control curves are defined in a form that is not too far from typical pressure control curves used in the particular types of applications. They serve only for the purpose of determining the EEI in the frame of the EPA. At the time this paper was written, different standardized pressure control curves belonging to different types of applications were considered by the EUROPUMP working group developing the EPA. For detailed information on the status of these discussions it is recommended to refer to [8].

In the present paper, the pressure control curve (as shown in Fig. 2)

$$\frac{H_i}{H_{100\%}} = \frac{1}{2} \frac{Q_i}{Q_{100\%}} + \frac{1}{2} \quad (3)$$

is used to illustrate the determination of EEI for variable-speed pump units. The pressure control curve according to Eq. (3) is illustrated in Fig. 2 as a red dashed line and takes into account that in typical real applications some static head needs to be maintained even if the flow rate is reduced to very small values. It should be noted that although the restriction to this pressure control curve clearly affects the numerical values of EEI, the general methodologies to determine the EEI presented in this paper are valid independently of a particular pressure control curve.

Energy-Efficiency-Index

The Energy-Efficiency-Index (EEI) is the result of the qualification of pump units in terms of energy efficiency according to the EPA described above. The EEI is defined in such a way that a dimensionless value representing the energy efficiency of the performance of a fixed- or variable-speed pump unit used in a particular type of application is established. Thus, also an additional aspect of competition is introduced (in comparison to a system of minimum required efficiencies only, e.g. MEI- [6] and IE-classes [7]) by showing the effect of the whole configuration of a pump unit on its energy consumption in different types of applications.

The EEI is defined as

$$EEI = \frac{P_{1,avg}}{P_{1,ref}} \quad (4)$$

where $P_{1,avg}$ is a weighted average of the electrical power input of the actual pump unit (either fixed- or variable-speed) and $P_{1,ref}$ denotes a reference electrical power input of a reference fixed-speed pump unit (c.f. Fig. 3). The wording “actual pump unit” denotes the really existing pump unit the EEI shall be determined for while “reference pump unit” denotes a virtual pump unit that is used to normalize the power consumption of the actual pump unit for the purpose of EEI determination in this paper.

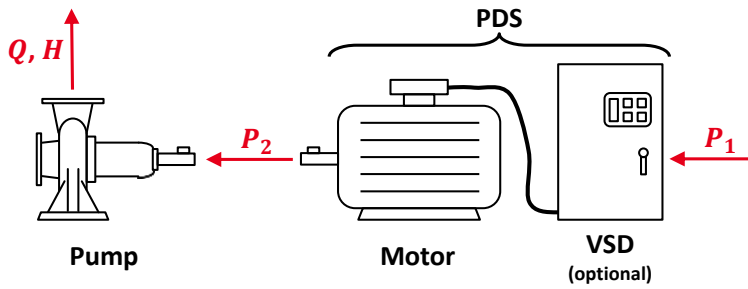


Fig. 3: Conversion of power between the components of a pump unit

The averaged electrical power input of the actual pump unit in the nominator of Eq. (4) is defined as the sum of the electrical power input values $P_{1,i}$ of the actual pump unit at each duty point of a load-time profile where the value of each duty point is weighted by the time fraction $\Delta t_i/t_{tot}$:

$$P_{1,avg} = \sum_i \frac{\Delta t_i}{t_{tot}} P_{1,i} \quad (5)$$

Generally, two methodologies for determining the electrical power input of the actual pump unit $P_{1,i}$ in Eq. (5) are possible. These experimental and semi-analytic approaches are described in chapters following below.

The reference electrical power input $P_{1,ref}$ in the denominator of Eq. (4) is established upon a (virtual) reference fixed-speed pump unit (without VSD). It is defined in a way to be independent from technical particularities of individual (existing) pump units and serves to normalize the values of the EEI in order to compensate physical and technological differences on maximum attainable energy efficiencies. Hereby pump units of different type, size and nominal data, but of the same quality of energy efficiency, will have comparable numerical values of EEI for the same load-time profile and pressure control curve.

The EPA has been developed (and is still under development) for very different kinds of product groups, e.g. circulator pumps, clean water pump units (equipped with one rotodynamic pump) or booster stations (equipped with more than one clean water pump unit). As these different kinds of extended products generally require specific measures of normalizing the EEI, the reference electrical power input $P_{1,ref}$ in the denominator of Eq. (4) needs to be defined separately for each of them. For the product group “clean water pump units (equipped with one rotodynamic pump)” covered by this paper, the reference electrical power input is defined as

$$P_{1,ref} = \frac{P_{2,ref}}{\eta_{Mot,ref}} \quad (6)$$

where $P_{2,ref}$ is a reference mechanical shaft power of a (virtual) reference pump unit while $\eta_{Mot,ref}$ denotes the efficiency of a (virtual) reference asynchronous motor. The reference mechanical shaft power in Eq. (6) is derived from a reference hydraulic power $\rho g Q_{100\%} H_{100\%}$, characterized by the nominal flow rate and the nominal head of the (existing) actual pump unit (which are identical to the values at the best efficiency point at nominal rotational speed $n_{100\%}$ of the actual pump), and the efficiency of a (virtual) rotodynamic reference pump $\eta_{Pump,ref}$:

$$P_{2,ref} = \frac{\rho g Q_{100\%} H_{100\%}}{\eta_{Pump,ref}} \quad (7)$$

The efficiencies of the (virtual) reference pump $\eta_{Pump,ref}$ and motor $\eta_{Mot,ref}$ in Eq. (6) and Eq. (7) are determined according to already existing product-specific efficiency standards to incorporate well established efficiency values of these components as base of the (virtual) components the (virtual) reference fixed-speed pump unit is composed of. The reference pump efficiency

$$\eta_{Pump,ref} = \eta_{Pump,ref} \left(Type, MEI, n_{100\%}, Q_{100\%}, H_{100\%} \right) \quad (8)$$

is derived from equations defined in a legislative regulation and a coming EN standard which concern the Minimum-Efficiency-Index (MEI) for clean water pumps ([4], [6]). The coefficients used in the equations therein and hence the reference pump efficiency as their result depend on the type of the (existing) actual rotodynamic pump (e.g. single-stage pump, multistage pump, inline pump), its nominal rotational speed $n_{100\%}$ and hydraulic quantities $Q_{100\%}$ and $H_{100\%}$ and a fixed value of the MEI the (virtual) reference pump shall exactly fulfill. The reference motor efficiency

$$\eta_{Mot,ref} = \eta_{Mot,ref} \left(f_1, N_p, IE, P_{2,ref} \right) \quad (9)$$

is derived from the calculation procedures defined in an IEC standard that concerns the IE classes system for asynchronous motors [7]. The procedures therein and hence the reference motor efficiency depend on the frequency of the electrical grid supplying the (existing) actual pump unit f_1 , the pole pair number of the (existing) actual asynchronous motor N_p , a fixed IE class the (virtual) reference motor shall exactly fulfill and the reference shaft power $P_{2,ref}$ that has to be determined according to Eq. (7) in advance.

The EUROPUMP working group developing the EPA for clean water pumps has not finally fixed the MEI value and IE-class the (virtual) reference components shall exactly fulfill in the definitions of $\eta_{Pump,ref}$ and $\eta_{Mot,ref}$. According to a proposal of the working group, a MEI value of 0.4 and class IE3 are used to evaluate $P_{1,ref}$ in the numerical examples in the subsequent chapters of this paper. Although these restrictions clearly affect the numerical values used in the examples, the general procedure to determine $P_{1,ref}$ is valid independently of particularly chosen MEI values and IE classes.

The definition of the reference electrical power input $P_{1,ref}$ can be summarized as follows:

The reference electrical power input $P_{1,ref}$ is the electrical power input to a (virtual) reference fixed-speed pump unit (without VSD). The reference unit has the same nominal rotational

speed ($n_{100\%}$) and hydraulic quantities (pump type, $Q_{100\%}$, $H_{100\%}$) as the (existing) actual fixed- or variable-speed pump unit the EEI shall be calculated for. The reference unit consists of state-of-the-art components as they are defined by means of existing product-specific standards (MEI, [6] and IE, [7]).

The reference electrical power input $P_{1,ref}$ is the electrical power input to this established (virtual) reference fixed-speed pump unit when its operation at nominal hydraulic conditions (characterized by $Q_{100\%}$ and $H_{100\%}$ of the existing actual pump unit) is considered. Hence, the reference electrical power input $P_{1,ref}$ rests upon nominal information on the rotodynamic pump of the (existing) actual fixed- or variable-speed pump unit only. It can be determined entirely based on information given in the product documentations as consequence.

Experimental Approach

The experimental approach to determine the EEI is straightforward: The fixed- or variable-speed pump unit to investigate has to be installed on a test bench. For the tests to be done, suitable measurement equipment to determine the electrical input power P_1 and the hydraulic output power characterized by the flow rate Q and the pump head H has to be available. Besides these primary measurement quantities, additional measurement equipment might be necessary to prove that standardized test conditions are fulfilled which will be described in future standards on EEI.

The duty points $Q_i/Q_{100\%}$ of the load-time profile (e.g. the load-time profile for closed loop applications, c.f. Fig. 2 and Tab. 1) must be adjusted by throttling and in case of variable-speed pumps additionally by adjusting the rotational speed in order to follow the standardized pressure control curve (e.g. the pressure control curve according to Eq. (3) and Fig. 2). For each duty point the electrical power input to the actual pump unit $P_{1,i}$ must be measured. Afterwards, the averaged electrical power input $P_{1,avg}$ can be determined from the measured $P_{1,i}$ values according to Eq. (5).

To use Eq. (4) and calculate the EEI, the reference electrical power input $P_{1,ref}$ has to be determined as well. The only information necessary to determine $P_{1,ref}$ is the nominal data of the rotodynamic pump of the actual fixed- or variable-speed pump unit. This information serves to establish the (virtual) reference fixed-speed pump unit belonging to the (existing) actual fixed- or variable-speed pump unit and can easily be found e.g. in the product documentation. As no measured data is necessary to establish $P_{1,ref}$, this reference value could also be calculated before the experimental investigation.

In the last step, the EEI for the (existing) actual fixed- or variable-speed pump unit can be calculated by means of Eq. (4).

This experimental approach is straightforward, but causes high effort especially when an actual pump unit equipped with components delivered by different manufacturers is considered.

Semi-Analytical Approach

The main motivations for the development of the semi-analytic methodology as an alternative to experimentally determine the EEI were

- to reduce the experimental effort to establish a market-wide EEI determination for pump units and
- to enable (or ease) generally a systematic determination of EEI values for units consisting of components delivered by completely different manufacturers.

The aim of the general procedure is to determine the electrical power input values $P_{1,i}$ to the actual pump unit at each duty point of the load-time profile by means of semi-analytic models (SAM). This method is developed within a project carried out at the Technische Universität Darmstadt. The project was initiated and is supported by EUROPUMP. It aims at the theoretical elaboration and experimental validation of the SAM method in the frame of the EPA for pump units.

When applying this method, the performance of the actual pump unit – and finally its electric power consumption – is mathematically synthesized using modeling of its particular components and taking into account the physical interactions of the components. The model of the pump unit is called semi-analytical because the mathematical correlations used describe the performance in a principal form that reflects the underlying physical processes and influences, but only needs a small amount of well-defined data from the separate components. These so-called supporting points serve to “calibrate” the principal equations describing the performance of both components (rotodynamic pump and PDS) to the investigated components.

The general calculation procedure by means of the SAM of the pump unit as well as the location of the supporting points of pump (blue upward-triangles) respectively PDS (purple downward-triangles) are illustrated in Fig. 4. The SAM of the pump unit consists of a SAM of the pump that is based on physical knowledge (affinity laws for rotodynamic pumps) and an empirical interpolation procedure for the losses of the PDS.

In case of the pump, the three supporting points correspond to the three duty points defined in the frame of the MEI (c.f. [6]), namely one at 75 % part load, one at 110 % over load and one at best efficiency point (BEP) of the pump. In case of the PDS the supporting points are different: They correspond to three out of eight supporting points which will be defined by [10] that form the corners of a characteristic triangle in the $n-T$ -plane containing the typical operation conditions of rotodynamic pumps. The supporting points of the PDS will be available (i.e. indicated in the product documentations) or at least calculable for each PDS on the market in the future.

In the end, the main purpose of both the SAM of the pump and the interpolation procedure for the losses of the PDS is to enable a prediction of the performance of both components at the duty points of the load-time profile on base of only these three supporting points per component. The physical and empirical knowledge about the components' part load behaviors representing the basement of the modeling enables sufficiently accurate predictions despite of the low numbers of supporting points. Although validation of the SAM methodology has not been finally accomplished at the time this paper was written, latest results in determining the EEI by means of the SAM methodology show deviations from experimentally determined EEI values only in the order of magnitude of typical total (systematic + statistic) measurement uncertainties.

The SAM calculation procedure is presented very basically in this paper: The SAM of the pump and the interpolation procedure for the losses of the PDS are treated as black-box models (input-output models) without giving detailed information about their internal mathematics (c.f. Fig. 4). At the time this paper was written, such details about the SAM of the pump respectively interpolation procedure for the losses of the PDS were still under consideration by the EUROPUMP working group developing the EPA for clean water pumps and will be described in a future standard on EPA for pump units once they are finally validated. Nevertheless, the general procedure of determining the EEI by means of the SAM method has been fixed by the working group so that further changes of details inside the black-box models of pump and PDS will improve the accuracy of predicting the numerical value of EEI but not affect the general procedure presented here.

In the following, the principal calculation procedure to determine the EEI of a pump unit by means of the SAM methodology will be explained in a numerical example. For this purpose, a fictitious variable-speed pump unit is utilized. The unit's nominal data is listed in Tab. 2 for convenience. Especially note that in case of the SAM method, a strict distinction between the nominal values of the pump and the nominal values of the PDS needs to be utilized. To facilitate the distinction, the subscript 100%, *Pump* will replace the subscript 100% used above for nominal values of the pump and 100%, *PDS* will indicate nominal values of the PDS in the following. The fictitious pump unit used in this numerical example does not correspond to any pump unit investigated at TU Darmstadt within the EUROPUMP project.

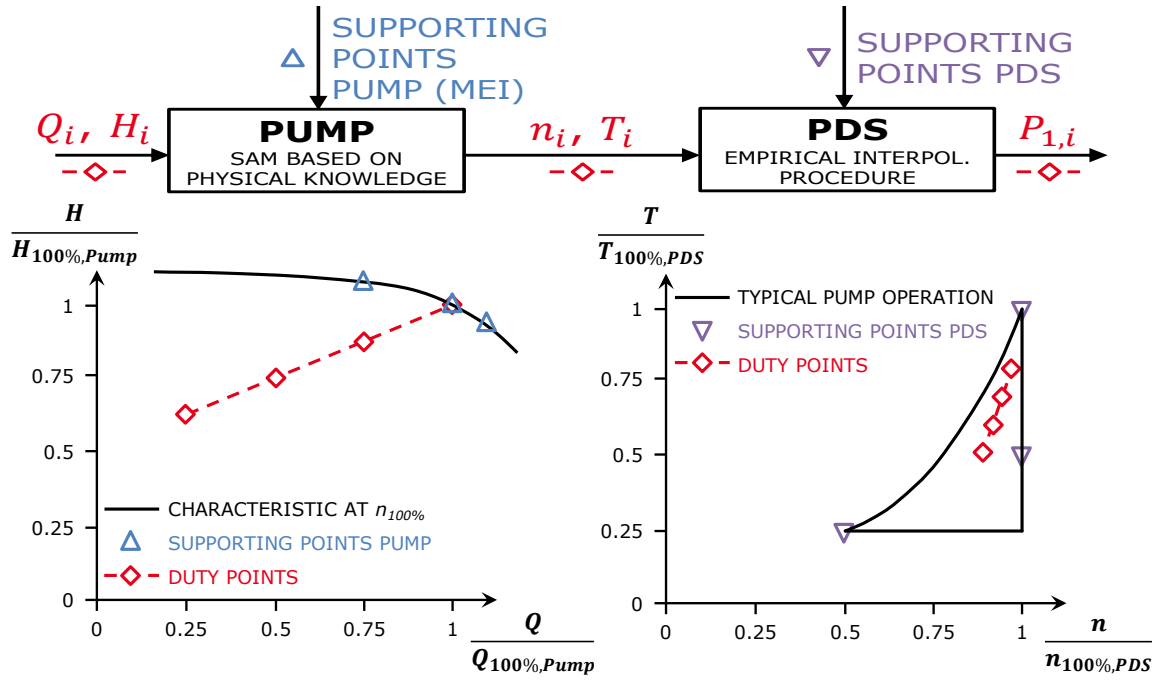


Fig. 4: Structure and supporting points of the semi-analytic methodology

The fictitious pump unit is equipped with a so-called “vertical multistage” (MS) pump with 3 stages and a 2-pole asynchronous motor. Because of the 2-pole asynchronous motor ($N_p = 1$), $n_{100\%, Pump} = 2900$ rpm has to be chosen as nominal rotational speed of the pump according to Eq. (2).

In contrast, the nominal rotational speed of the PDS corresponds to the nominal load condition of the PDS where the nominal mechanical power $P_{2,100\%, PDS}$ and nominal torque $T_{100\%, PDS}$ of the PDS are delivered simultaneously. Therefore, $n_{100\%, PDS}$ represents a design value of the PDS and is individual for each PDS. The nominal data of the fictitious PDS used in this numerical example is listed in Tab. 2, too.

The EEI in this numerical example will be determined on base of the closed loop load-time profile (c.f. Fig. 2, Tab. 1) and, as a variable-speed pump unit is considered, the pressure control curve defined by Eq. (3).

Tab. 2: Nominal data of fictitious variable-speed pump unit

Pump Type	$Q_{100\%, Pump}$	$H_{100\%, Pump}$	$n_{100\%, Pump}$	$T_{100\%, Pump}$	$P_{2,100\%, Pump}$
MS ($N_{Stages} = 3$)	49.7 m ³ /h	54.7 m	2900 rpm	38.2 Nm	11.6 kW
N_p	Variable Speed Drive?	$n_{100\%, PDS}$	$T_{100\%, PDS}$	$P_{2,100\%, PDS}$	
1	yes	2926 rpm	49.0 Nm	15.0 kW	

The supporting points for the components of the fictitious pump unit which need to be available for application of the SAM method are given in Tab. 3. The three supporting points of the pump (defined by the rated flow rate $Q / Q_{100\%, Pump}$) are given in the left table, while the three supporting points of

the PDS (defined by the relative speed $n/n_{100\%,PDS}$ and relative torque $T/T_{100\%,PDS}$) are given in the right table. The performance-characterizing values of the pump that need to be known for each supporting point are the rated head $H/H_{100\%,Pump}$ and the rated mechanical power $P_2/P_{2,100\%,Pump}$, the respective values of the PDS are the so-called related losses $p_{L,PDS} = P_{L,PDS}/P_{2,100\%,PDS}$. These are dimensionless values that indicate the magnitude of the absolute losses of the PDS $P_{L,PDS}$ at an operating point in relation to the nominal mechanical power of the PDS $P_{2,100\%,PDS}$.

Tab. 3: Supporting points of pump and PDS of fictitious variable-speed pump unit

$Q/Q_{100\%,Pump}$	$H/H_{100\%,Pump}$	$P_2/P_{2,100\%,Pump}$	$n/n_{100\%,PDS}$	$T/T_{100\%,PDS}$	$P_{L,PDS}$
0.75	1.14	0.91	1	1	17 %
1	1	1	1	0.5	9 %
1.1	0.93	1.03	0.5	0.25	4 %

Application of the SAM of the Pump

In a first step, the values of rotational speed n_i and torque T_i corresponding to the load points Q_i and H_i defined by the closed loop load-time profile and pressure control curve defined by Eq. (3) need to be determined. For this purpose, the SAM of the pump is adjusted to the actual pump of the fictitious pump unit by means of the pump's supporting points listed in Tab. 3. After this, the mechanical representation of the load points can be calculated by means of the SAM of the pump. This is given relative to the pump's nominal point in Tab. 4.

Tab. 4: Results of the SAM of the pump

$Q_i/Q_{100\%,Pump}$	$n_i/n_{100\%,Pump}$	$T_i/T_{100\%,Pump}$	$P_{2,i}/P_{2,100\%,Pump}$
1	1	1	1
0.75	0.90	0.78	0.70
0.5	0.80	0.55	0.44
0.25	0.72	0.35	0.25

Application of the interpolation procedure of the PDS

The values of speed n_i and torque T_i calculated by the pump SAM serve as input data to the interpolation procedure of the PDS. As the nominal points of the pump and the PDS are defined in different ways, the mechanical load points given in a representation relative to the pump's nominal point in Tab. 4 have to be converted to a form relative to the nominal point of the PDS first:

$$\frac{x_i}{x_{100\%,PDS}} = \frac{x_i}{x_{100\%,Pump}} \frac{x_{100\%,Pump}}{x_{100\%,PDS}} \quad (10)$$

In the next step, the related losses $p_{L,PDS,i}$ have to be determined for the mechanical load points. For this purpose, the interpolation procedure for the losses of the PDS is adjusted to the actual PDS of the fictitious pump unit by means of the supporting points of the PDS given in Tab. 3. The results of the interpolation scheme of the PDS as well as the mechanical load points in their representation converted according to Eq. (10) are given in Tab. 5. Note that for better orientation the rated flow rates are still given in their form relative to the pump's nominal point in Tab. 5.

Tab. 5: Converted mechanical load points and calculated losses of the PDS

$Q_i / Q_{100\%, Pump}$	$n_i / n_{100\%, PDS}$	$T_i / T_{100\%, PDS}$	$P_{L, PDS, i}$
1	0.99	0.78	13.8 %
0.75	0.89	0.60	10.7 %
0.5	0.79	0.42	7.6 %
0.25	0.71	0.27	5.1 %

Combination of the Results

To finally determine the electrical power input $P_{1,i}$ at each load point n_i and T_i respectively Q_i and H_i , the results from the SAM of the pump (Tab. 4) and the interpolated losses of the PDS (Tab. 5) have to be combined. Note that the respective nominal values the individual results are referred to have to be considered during this combination:

$$P_{1,i} = P_{2,i} + P_{L, PDS, i} = \frac{P_{2,i}}{P_{2,100\%, Pump}} P_{2,100\%, Pump} + P_{L, PDS, i} P_{2,100\%, Mot} \quad (11)$$

The combined results respectively the searched electrical power input values $P_{1,i}$ to the fictitious pump unit for each load point of the closed loop load-time profile and for the pressure control curve defined by Eq. (3) are listed in Tab. 6.

Tab. 6: Combined results of the calculations for the pump and the PDS

$Q_i / Q_{100\%, Pump}$	$P_{1,i}$
1	13.7 kW
0.75	9.7 kW
0.5	6.2 kW
0.25	3.7 kW

From these results, the averaged electrical power input to the fictitious variable-speed pump unit can be determined as

$$P_{1,avg} = 0.06 P_{1,100\%} + 0.15 P_{1,75\%} + 0.35 P_{1,50\%} + 0.44 P_{1,25\%} \approx 6.1 \text{ kW} \quad (12)$$

Calculation of the Energy-Efficiency-Index

The reference electrical power input $P_{1,ref}$ of the (virtual) reference fixed-speed pump unit corresponding to the fictitious actual variable-speed pump unit investigated in this numerical example must be calculated before the EEI can be determined for it. Note that the determination of $P_{1,ref}$ is based on nominal information on the actual rotodynamic pump only. These can easily be found e.g. in the product documentations. Hence, the value of $P_{1,ref}$ could have been calculated before the determination of $P_{1,avg}$ as well.

The procedures to determine $\eta_{Pump,ref}$ and $\eta_{Mot,ref}$ inside the calculation of $P_{1,ref}$ would lengthen this paper obviously and are therefore left out here. They are described in detail in [6] and [7]. Along with

the intermediate results $\eta_{Pump,ref} \approx 70.7\%$ (calculated by means of [6]), $P_{2,ref} \approx 10.5\text{ kW}$ (calculated by means of Eq. (7)) and $\eta_{Mot,ref} \approx 91.0\%$ (calculated by means of [7]), the reference electrical power input corresponding to the actual pump unit investigated in this numerical example can finally be determined as $P_{1,ref} \approx 11.5\text{ kW}$

With the averaged electrical power input determined by means of the SAM and the reference electrical power input calculated just before, the EEI determined on base of the closed loop load-time profile and the pressure control curve defined by Eq. (3) can finally be calculated for the fictitious actual variable-speed pump unit as $EEI \approx 0.530$ in this numerical example.

Outlook

After European legislative regulations started ascertaining and prescribing minimal levels of the efficiencies of pumps within the frame of the Product Approach in January, 2013, the European energy efficiency strategy might aim at the very often used combinations of rotodynamic pumps and asynchronous motors with and without Variable Speed Drives (e.g. frequency converters) in the frame of the Extended Product Approach in the future. If the Extended Product Approach will be introduced in European legislation and standardization, the methodologies to determine the EEI presented in this paper might be applied by manufacturers or suppliers of pump units to determine the EEI-values of the pump units they place on the market or put into service.

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