AN APPROACH TO THE EVALUATION OF THE ENERGY EFFICIENCY OF MACHINES BASED ON DIGITAL TWINS AND SIMULATION METHODS

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ABSTRACT

This paper presents an approach to evaluating the energy efficiency of hydraulic machines using digital twins and simulation methods. It emphasizes the importance of considering the entire life cycle of a product and minimizing power consumption of a hydraulic system during its development. Additionally, sustainability activities at Bosch Rexroth are presented and upcoming legal requirements are discussed. By utilizing digital twins, which contain simulation models, the dynamic and efficiency behavior of the machines can be investigated. Through a visualization of energy flow based on simulation results, opportunities for energy savings are identified. Overall, this contribution showcases the benefits of digital twins in optimizing energy consumption and promoting sustainability in the industrial sector.

Keywords: System simulation, energy efficiency, sustainability, carbon footprint

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1. INTRODUCTION

Sustainability has been gaining in importance in all areas of society for several years. Therefore, OEMs, machine operators, government and society expect extensive activities from machinery suppliers. Bosch Rexroth has taken this challenge and pursues a holistic approach from cradle to grave. This means that the whole life cycle of a product is considered, i.e., from raw material mining up to recycling. Therefore, tools for the quantification of sustainability measures like product carbon footprint were developed and are used during product development and manufacturing.

In the industrial sector, the operating phase of a machine is of particular importance, as it has a massive impact on the CO2 emissions, whereas in the sector of consumer goods, it is often the manufacturing phase that is more significant. Hence, the power consumption of machines used in industrial production should be already considered and minimized during development. This applies especially to hydraulic machines such as presses and injection molding machines, which often have a high energy consumption.

However, a component-based approach alone is not meaningful. Instead, the interaction of the entire machinery must be considered, and the energy consumption is strongly dependent on the used cycle. Without the usage of digital twins, the energy consumption can hardly be calculated before commissioning, especially since norm cycles are not always defined. Therefore, Bosch Rexroth has recognized this demand and provides digital twins containing simulation models for many products, which allow to investigate the dynamic and efficiency behavior. An automatic visualization of the energy flow based on the simulation results helps to gain further insights and to uncover savings opportunities. The machinery builder can compare different machinery setups regarding energy consumption and thus find an optimal setup.

In this contribution, first the current societal and legal framework conditions regarding sustainability and energy efficiency are examined. Subsequently, the possibilities of energy-efficient drives from Bosch Rexroth are presented, and the necessity of a simulation-based approach is motivated. Afterwards the Rexroth Simulation Library BRSL is introduced, which provides a variety of digital twins for Rexroth products. Following this, an application is presented, which allows a clear visualization of the system's energy flows. Subsequently, the capabilities of the simulation-based approach for the energetic analysis are demonstrated using a practical example, namely the retrofit of a block press. Therefore, the importance of visualizing the energy flow is particularly emphasized. Finally, the main contents of the article are summarized, and an outlook on future activities is given.

2. LEGAL ASPECTS REGARDING SUSTAINABILITY AND ENERGY EFFICIENCY

Companies are faced with expectations regarding sustainability from various sides. Many investors demand compliance with ESG (Environment, Social and Governance) criteria. In addition to good working conditions, employees seek for a meaningful corporate purpose. Achieving the climate targets requires significant efforts to reduce energy consumption. In the current energy price environment efficiency increases are strictly necessary in order to maintain competitiveness. End customers are becoming increasingly responsible and consider the exact ecological footprint of a product in their purchasing decisions. Summing it up, the subject area of sustainability covers a huge variety of aspects that are important in mechanical and plant engineering. Among others these are resource efficiency, safety and health, emission reduction, energy efficiency and ethical aspects. To provide a comprehensive overview of the entire field of sustainability and all the legal framework conditions would go beyond the scope of this article. Therefore, only the most important points for the fluid industry in Germany from the authors' point of view are discussed below.

A crucial factor in gaining an overview of this multitude of aspects is a systematic approach. Therefore, the creation of a Life Cycle Assessment (LCA) in accordance with DIN EN ISO 14040 [1] yields a good starting point. The norm specifies that an LCA should consider the entire life cycle of a product or service, from the extraction of raw materials through production and use to disposal. The aim is to assess and reduce environmental impacts. The standard serves as a guide for companies and organizations to improve their environmental performance and make more sustainable decisions. This involves an input and output analysis of value streams. One of these value streams is, for example, energy consumption. Bosch Rexroth has developed internal tools for this purpose, in order to display the resource expenditure and thus the ecological footprint as accurately as possible from cradle to gate.

The use of environmentally hazardous substances is often prohibited or restricted by law. For example, the currently discussed ban of PFAS materials, which are very important for sealing technology. In terms of total CO2 emissions, the operating phase is more important than the production phase for industrial equipment. For this reason, there are government funding programs for new systems with higher energy efficiency as well as statutory minimum requirements in mechanical and plant engineering. In Germany, for example, the retrofit of hydraulic systems with energy-efficient variable-speed drives could be subsidized by Federal Office of Economics and Export Control [2].

The most important legal requirements result from the eco-design directive 2009/125/EC of the European Union [3]. This directive is intended to ensure that energy related products on the European market meet certain minimum energy efficiency requirements. To this end, certain product groups are defined for which regulations are successively being established.

The requirements arising from this regulation are steadily increasing. Certain requirements for fluid power systems are not yet specified. Therefore, the eco-design regulation (EU) 2019/1781 [4] for electric drives is the most important for fluid industry, since most hydraulic pumps within industry hydraulics are driven by asynchronous drives. In addition to the requirement of efficiency class IE4 for direct-fed asynchronous motors, the current version also defines minimum requirements for asynchronous motors in frequency converter operation. It is conceivable that in future the system limits will be defined more broadly and that the hydraulic pump will also be considered. This would mean that like the product class compressor, requirements would also be made on the efficiency of a hydraulic power unit. In addition to regulations, the eco-design directive also allows self-regulation if the sector targets are met.

A component-based approach to the evaluation of energy efficiency is not considered appropriate in the field of fluid technology. For example, if a very efficient hydraulic power unit is used in a valve-controlled system with very high throttling losses, the overall efficiency is still low. Another challenging aspect of the overall system analysis is that there are only defined standard cycles for a few machine types and the actual energy consumption also depends on the used cycle. For injection molding machines characteristic cycles were defined with EUROMAP60 [5]. But there is no standard cycle that applies to all hydraulic systems, such as the WLTP in the automotive industry, due to the great variance and different applications.

Hence, neither a component-based approach nor absolute efficiency requirements at system level are appropriate. However, a mandatory energy assessment of the overall system could lead to the required energy savings. This could be carried out on a real test system or virtually with the usage of digital twins.

3. ENERGY EFFICIENT DRIVES FROM BOSCH REXROTH

The classification of the basic circuits of electrohydraulic drives according to Backé offers a systematic approach to the different drive technologies of the fluid industry [6]. For this purpose, a differentiation is made between systems with impressed volume flow and systems with impressed pressure on the one hand and resistance or displacement controls on the other hand.

All these four drive concepts have their system-related advantages and disadvantages and their respective application purpose. For example, secondary controlled drives are usually used for winches, whereas throttle-controlled drives are used for injection molding machines. In general, resistance-controlled drives offer higher dynamics compared to displacement-controlled drives, but also lower energy efficiency. As a fullliner, Bosch Rexroth offers a wide range of products that can be combined to create energy-efficient hydraulic drives.

Figure 1: Technological development in hydraulic drives

The long-term trend that can be observed in the fluid industry is shown in **Figure 1** above. Development began with central hydraulic power units, which provide the power centrally for all consumers. The next stage of development was to provide on-demand volume flow directly at the actuator. Finally, this led to highly integrated compact actuators, which can hardly be distinguished from an electric actuator by their interface.

Furthermore, various new approaches have also emerged from the academic environment to increase energy efficiency, for example high-pressure hydraulics, digital hydraulics, or dissolved control edges.

However, detailed energy considerations for specific industrial applications go far beyond the theoretical analysis of drive concepts. For this purpose, different product classes such as asynchronous motors or synchronous motors or different types of pumps must be compared with each other down to individual details such as series and nominal sizes. Ultimately, this means that for the real energy assessment of the overall system, the analysis must be carried out down to the individual components used.

Regarding energy efficiency, two questions usually need to be answered when retrofitting an existing system or developing a new machine: Does the new drive concept meet the dynamic requirements? How big are the energy savings compared to the existing concept? This evaluation and cross-comparison between two drive systems is only possible either with real prototypes or with the help of simulation. Therefore, Bosch Rexroth has decided to start the development of a simulation library with the aim of providing digital twins for all relevant products.

4. BRSL – REXROTH SIMULATION LIBRARY

4.1. Overview

The Rexroth Simulation Library BRSL is a complete library for analyzing the static, dynamic and kinematic behavior of machines and systems. It allows the creation of a virtual representation of a system based on so-called digital twins of the components. The library contains both generic components, which can represent the behavior of components from different manufacturers using data sheets, and pre-parameterized models of Bosch Rexroth products. These pre-parameterized models are ready to use by default. They are fully validated by Bosch Rexroth and selected directly via the type code (see **Figure 2**). On the one hand, this has the advantage of eliminating the time required for parameterization, while at the same time preventing incorrect parameterization.

The BRSL is developed in the tool-independent modeling language Modelica [7], which results in direct compatibility with several widely used simulation tools available on the market. Using the FMI (Functional Mockup Interface) modeling standard [8], BRSL models can also be easily integrated into non-Modelica tools. The BRSL is officially released as a product, i.e. it is available to all users who want to benefit from the numerous well-known advantages of simulation usage.

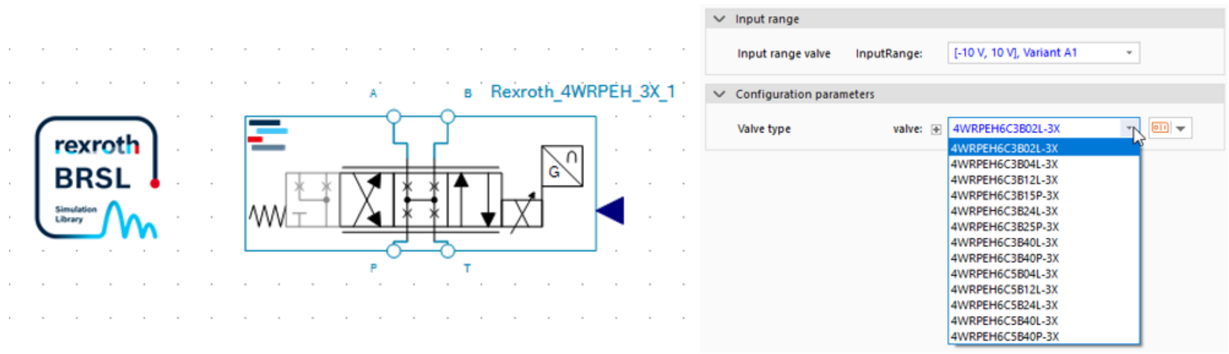

Figure 2: Parameter window for pre-parameterized Rexroth 4WRPEH valve model

4.2. Requirements for analyses of energy efficiency and carbon footprint

The BRSL models include all the physical effects required for the use in a 1D dynamic system simulation. This includes not only static operating limits of the components, but also dynamic effects such as friction and damping, pressure build-up behavior, pressure- and load-dependent switching times as well as frequency responses.

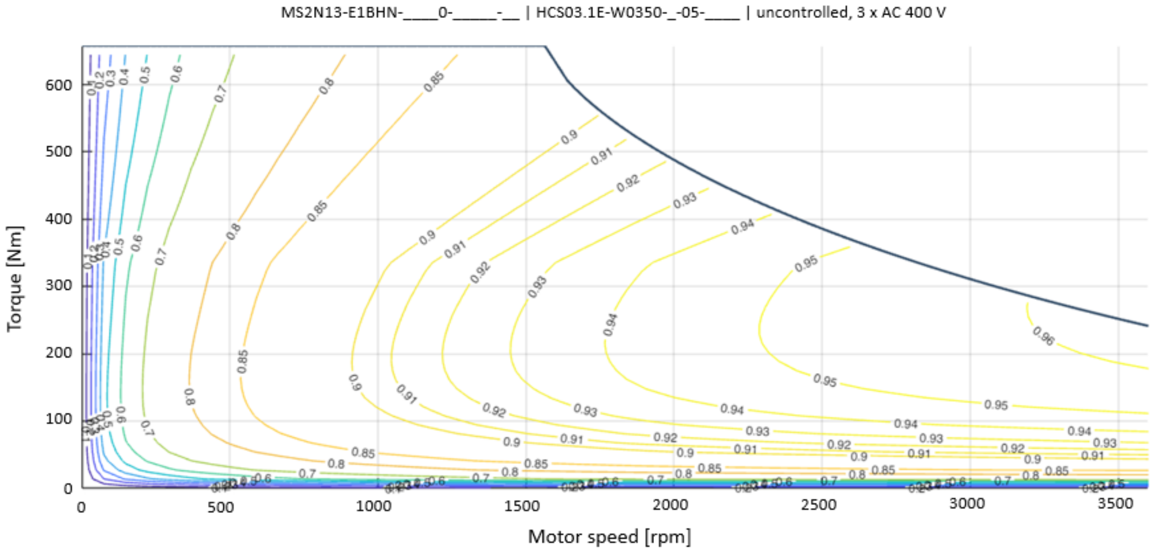

Figure 3: Efficiency characteristics for Rexroth MS2N13 motor with Rexroth HCS03 frequency converter over speed and torque

Of particular importance for energy efficiency and carbon footprint analyses is the inclusion of component losses. For this purpose, the individual product models within the BRSL contain detailed efficiency characteristics that include the efficiency as a function of relevant influencing variables. In the case of a hydraulic variable displacement pump, for example, these are pressure, speed and swivel angle. For an electric motor, however, these are speed and torque (see **Figure 3**). This includes all quadrants, so that recuperation effects can also be considered. The hydraulic losses within the components are also calculated for the generic hydraulic components; these can be calculated from the product of pressure loss and volume flow.

5. A MATLAB APPLICATION FOR ENERGY VISUALIZATION

5.1. Overview

Although the losses of the individual components are already included in the simulation models and hence in the simulation results, it is very difficult to analyze the energy household directly within the simulation tool. For this purpose, Bosch Rexroth has developed a MATLAB WebApp that clearly visualizes the energy losses of both the overall system and the contained components separately. The application allows to analyze one single system and to identify critical losses, but it is also possible to compare two systems with each other. In this case, energy savings and carbon footprint reductions become clearly visible.

As basis for the visualizations, simulation result files in CSV format are used. Currently, the tool is specifically tailored to the use of the BRSL, however, an extension to simulation models of other tools is feasible. For the analyses presented in this paper, simulations were carried out using models based on BRSL within the simulation software SimulationX by ESI Group.

5.2. Description of the different views of the application

After the start, a new empty project is automatically created. If it is desired to continue working on a previous analysis, this project can be loaded by using the corresponding button at the top of the application. In any case, the tool will start with the main project view, which allows to enter project-specific data. In addition to the project name, this also includes information on the project participants and the contact persons involved. The next step is to load the simulation results. It is possible to either load one file or – in case that two systems shall be compared – two different result files.

For the following analysis, the tool contains several views, each of which allows a different perspective on the data. The first view provides an overview of the input and output power of the individual components. These are displayed both over time and as a mean power value. This view, using the data from the example used in this paper, is shown in **Figure 6** in the Examples Section. In addition to the power, the energy consumed or emitted can also be displayed. Similarly, both the energy over time for the individual components and the mean value for a component are shown.

Furthermore, it is possible to display the energy sources and energy sinks separately in the form of pie charts (see **Figure 7** in the Example Section). This enables to determine the share of each component in the overall energy household of the system or machine. Another option is to display the data separately by domain (mechanic linear, mechanic rotary, hydraulic, electric). This emphasizes the system's energy converters. At the same time, it is possible to clearly show the resulting losses.

Finally, the tool contains a quantitative evaluation of the system, which, however, requires further input data. Firstly, the number of cycles per hour, the number of hours the machine runs per day and the number of days of operation per year must be specified. Secondly, it is necessary to specify the price per kWh of energy and the CO2 emissions in grams per kWh. Based on this, the annual energy consumption, the resulting costs and the CO2 emissions are calculated. If two systems are compared, the values just mentioned are calculated for both systems and the difference value, i.e. the saving, is shown. When also providing the investment costs for a retrofit with conversion of the system, for example, the ROI (Return on Investment) is derived directly from the savings. This view is shown in **Figure 8** in the Example Section.

To summarize, the application allows it to easily evaluate one or more machines in terms of energy consumption and, if necessary, to compare them with each other to quantify the savings potential.

6. APPLICATION TO A PRACTICAL EXAMPLE

This article presents the application of simulation and energy analysis for the economic evaluation of a retrofit of block press. This is a very common case in practice: there is already an existing system and the question arises whether it is economical converting the system to a more energy efficient one. To answer this, the investment costs must be compared with the financial savings resulting from higher energy efficiency. Therefore, however, it is first necessary to know the exact energy consumption of both systems, which can be determined using simulations. The following example is derived from a real industrial project.

6.1. Reference system – Valve-Driven System

The reference system is a press with a conventional valve drive. A schematic diagram is shown in **Figure 4**. It should be noted that this is a reduced view for the sake of clarity and that the simulation model used is more detailed. From a high-level perspective, the model consists of a hydraulic power unit, a valve for controlling the volume flow, a double-rod cylinder, a process model and a corresponding control algorithm.

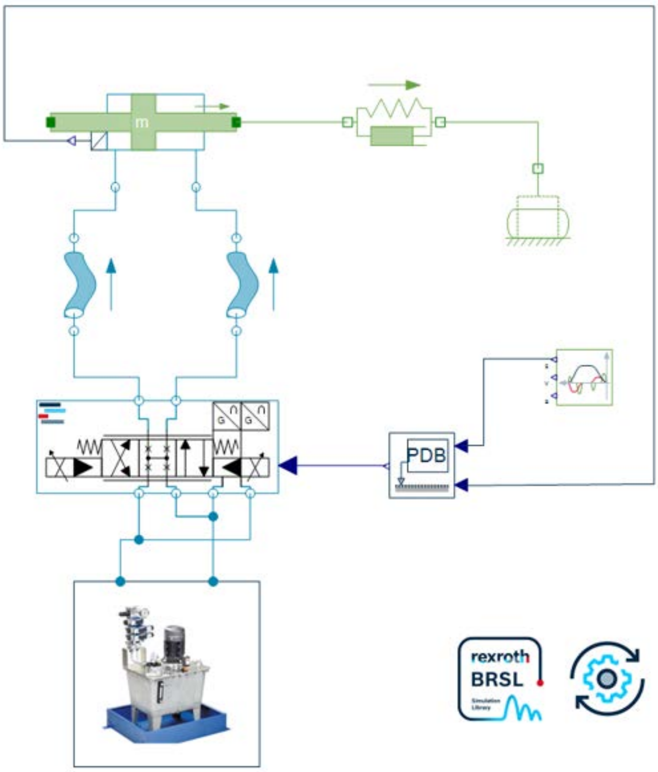

Figure 4: Schematic view of the reference system (simplified illustration)

The hydraulic power unit consists of a direct-fed asynchronous motor including efficiency characteristics, an axial piston pump with swivel angle control (Rexroth A4VSO), a hydraulic accumulator and a check valve. The process consists of pressing the blocks. To do this, the cylinder extends to an end position within a defined time and then returns to the start position. Including the waiting time for inserting the new material, one cycle takes approximately 4.5 seconds.

This system is suboptimal from an energy point of view, as the hydraulic power unit constantly provides a pressure of 200 bar, regardless of what is required by the process. The pressure that is not required is throttled at the valve. For this reason, the valve-driven system could be replaced by a more energy-efficient cylinder direct drive.

6.2. Optimized system – Cylinder Direct Drive

To optimize the system, the valve drive is replaced by a frequency-controlled pump drive in a closed circuit system. A simplified, schematic view of the optimized system is shown in **Figure 5**.

The drive consists of a synchronous motor (Rexroth MS2N13) with a suitable converter (Rexroth HMS01), which drives an axial piston pump for the closed circuit (Rexroth A4CSG). All components include efficiency characteristics. Two boost pumps are required in addition to the axial piston pump. Boost pump A is used for the pressure supply to the swiveling unit of the axial piston pump (not shown in simplified model view), boost pump B provides the necessary supply pressure for the closed loop system. Hence, the pump directly drives the double-rod cylinder, which interacts with the process. The cylinder, the process model and the control command values are identical to the reference model. Finally, the model also includes the necessary equipment for the closed circuit and hydraulic piping.

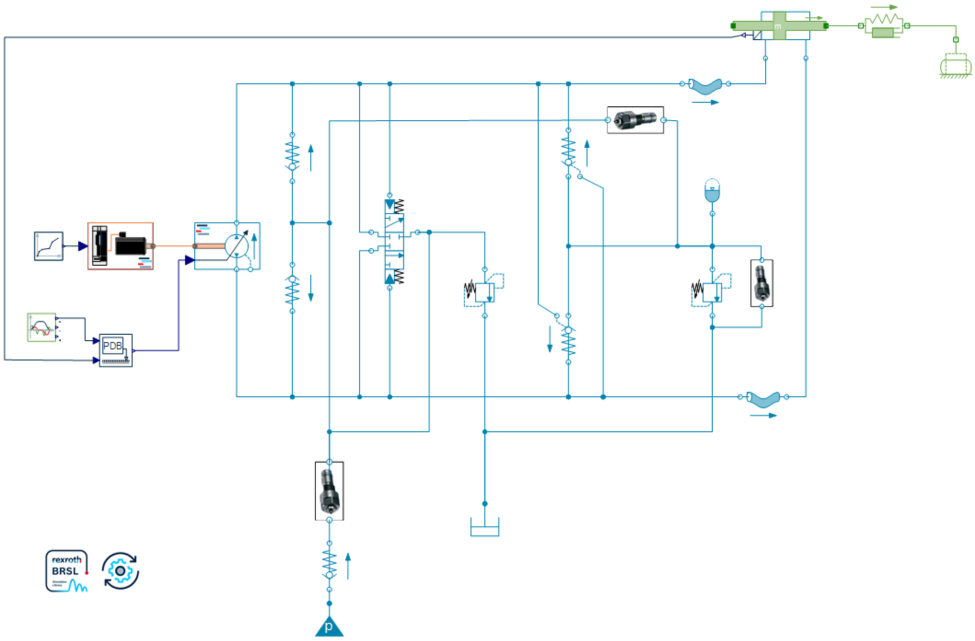

Figure 5: Schematic view of the optimized system (simplified illustration)

6.3. Results

The two systems described above, i.e. the reference system and the optimized system, were simulated with SimulationX and the results were saved in CSV format. Based on the simulation results, it was first verified that the requirements for accuracy and dynamics are fulfilled also in the optimized system setup.

The result files were then loaded into the MATLAB application for analyzing the energy household of the systems.

Power view

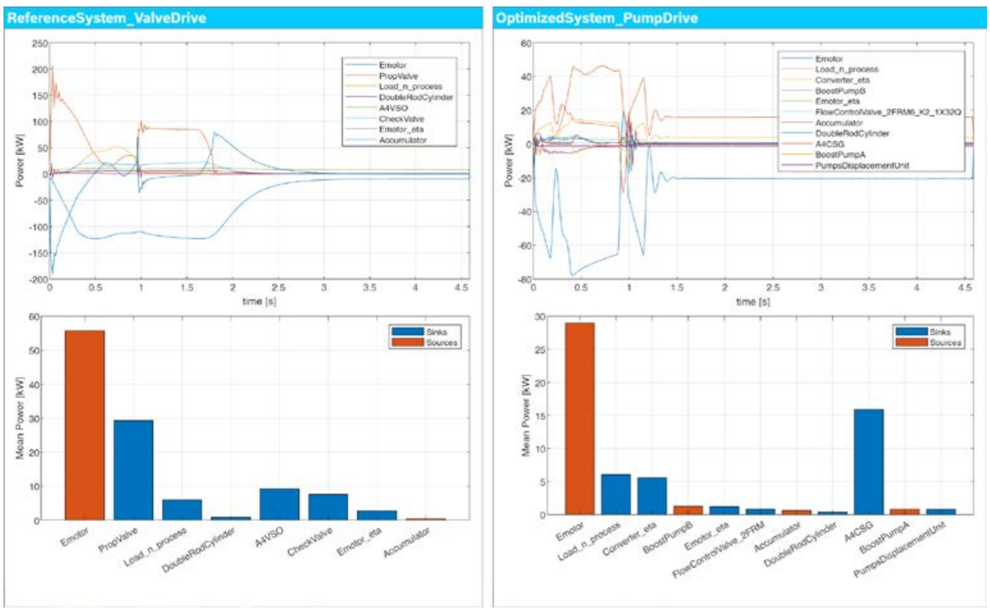

Figure 6: Power input and output of components (left: reference system, right: optimized system); upper graphs show the consumption over time, lower charts contain mean power values of components

The evaluation of the outputs (see **Figure 6**) shows that the average power of the electric motor, which is the main energy source in both systems, can be reduced from 58 kW to 29 kW as a result of the retrofit. This corresponds to a reduction of 50%. In the optimized system compared to the reference system, however, two additional energy sources (with relatively small impact) are available with the two boost pumps. The main consumer in the reference system is the proportional valve, with a mean power consumption of 29 kW. In the optimized system, the pump (A4CSG) has the highest share, but with 16 kW mean power this is below the consumption of the valve in the reference system.

Splitting by energy sources and energy sinks

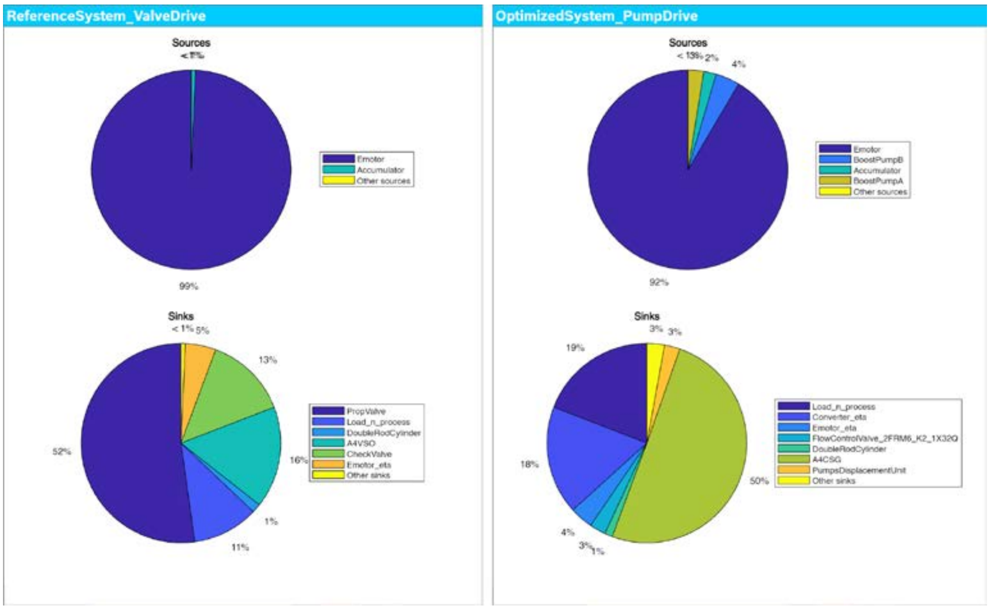

Figure 7: Visualization of energy sources and energy sinks using pie charts (left: reference system, right: optimized system)

Figure 7 shows the energy share of the individual components, broken down into energy sources and energy sinks. It becomes again visible that the electric motor is the main source of energy in both systems. In the reference system, the motor accounts for 99% of all energy sources, while in the optimized system it accounts for 92% (the two boost pumps account for 3% and 4% respectively).

In the case of energy sinks, it is desirable that the process has the highest possible share and that there are as few other, undesirable energy sinks as possible. The improvement in the optimized system is clearly visible in the diagrams. In the reference system, the process (Load_n_process) has a share of 11%, whereas in the optimized system it has increased to 19%. As previously mentioned, the main energy sinks for the two systems are the proportional valve and the axial piston pump, respectively. Both have a share of around 50% each.

It should be emphasized that this view does not show absolute values, but the relative share of energy sources or sinks in the respective household. The fact that the optimized system consumes less overall power was already apparent in the power view described above. This also means that a proportion of 50% in the optimized system means less energy consumption in absolute terms than a proportion of 50% in the reference system. This becomes also clear in the quantitative evaluation of both systems, which is described in the following section.

Quantitative evaluation of the savings

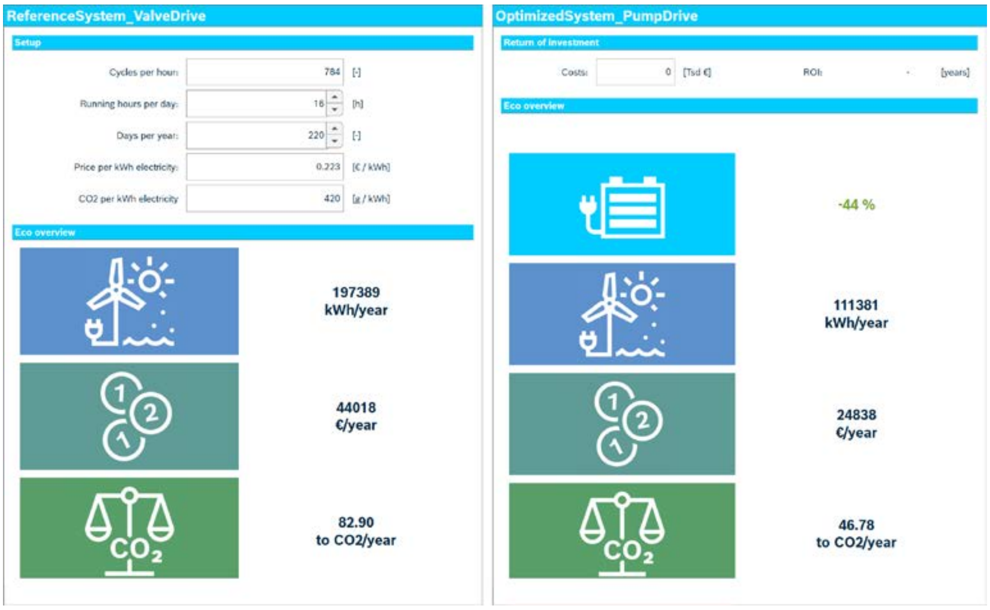

Figure 8: Quantitative comparison of the two systems with presentation of the savings (left: reference system, right: optimized system)

An overview of the quantitative comparison of the two systems is shown in **Figure 8**. In the upper left part of the figure, definitions regarding the machine runtime are specified. The process used in this example has a duration of slightly more than 4.5 seconds per cycle. Assuming continuous production, this results in 784 cycles per hour. It is further assumed that production takes place in two-shift operation (16 hours per day) and that the machine operates 220 days per year. The assumed price of 22.3 ct per kWh of energy and the CO2 emissions of 420 grams per kWh are also set there.

Based on the simulated energy required for the systems and the aforementioned data, the retrofit results in energy savings of 86008 kWh per year. This corresponds to yearly financial savings of 19180 €. Furthermore, 36.12 tonnes of CO2 per year can be saved. The total energy saving as a result of the retrofit is 44 %. These results correspond to the values measured on the real systems before and after the retrofit.

If the investment costs for the retrofit are additionally entered in the application, it is possible to calculate directly how fast the conversion will amortise financially. However, the economic view in relation to the ROI is not considered in this example.

7. SUMMARY AND OUTLOOK

7.1. Summary

In this contribution, the importance of increasing the energy efficiency of hydraulic systems and how this can be achieved through the usage of digital twins was discussed. The general trend towards sustainability, which is also being demanded by more and more customers, will confront industrial companies with significant challenges in the future. In addition, legal requirements are constantly increasing. A Life Cycle Assessment according to DIN EN ISO 14040 offers a systematic approach and important legal framework conditions are contained in eco-design directive 2009/125/EC of the European Union. This includes requirements for the energy efficiency of energy-related products. It was argued that a general component-based approach to the energy efficiency of hydraulic systems is not appropriate. Instead, when assessing the energy efficiency of a system, it is necessary to consider the interaction of all components, particularly taking into account the actual loads due to the machine cycle. Simulation methods are a suitable option for a simple and cost-effective realisation of this. With the simulation library BRSL, Bosch Rexroth provides digital twins for Bosch Rexroth components that enable virtual energy analyses without the use of real prototypes. Furthermore, a MATLAB application that evaluates energy flow based on simulation results was presented. The functionality of this approach, consisting of simulations with BRSL components and a subsequent evaluation with the MATLAB application, was demonstrated using a real industrial example, the retrofit of a block press. The quality of the simulated results was compared with real measurements before and after the retrofit and could be confirmed.

7.2. Outlook

In future, the presented approach will be used for other industrial projects at Bosch Rexroth to increase the energy efficiency of hydraulic systems. To enable this, the development of the BRSL simulation library will be continued in order to close existing gaps in the product portfolio and to be able to offer a digital twin for new products directly. Currently, the BRSL is only offered as one package containing all components and only Modelica-based tools are supported. To ensure wider availability, Bosch Rexroth is actively involved in the IDTA (Industrial Digital Twin Association) working group to enable tool-independent provision of component models via the simulation subaspect of the Asset Administration Shell [9].

However, hydraulic systems do not only contain components from Bosch Rexroth. Competitors are therefore also invited to provide simulation models for their products in order to offer machine builders a supplier-independent assessment of the energy consumption of systems.

The topic of sustainability is of particular importance to Bosch Rexroth. This is why Bosch Rexroth is continuously working on innovative methods for optimizing the energy efficiency of machines and systems. To support this, also new tools and methods such as the simulative approach for evaluating the energy efficiency of machines described in this contribution will be continuously developed.

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