Digitalization in Sustainability for Fluid Power Components and Systems

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Abstract.

Tracking energy losses and global warming potential (GWP) in mobile hydraulic machines and individual components is of growing importance due to an increase in regulations limiting the total GWP of operations and products. Based on data from a wheel loader performing a Y-cycle load operation, this paper computes the energy flow within the hydraulic system using a combination of measurements and system simulation. The energy flow can be used for system optimization. The calculated energy losses and GWP are shared with actors along the value chain using the Asset Administration Shell.

Keywords. Digitalization, simulation, asset administration shell, global warming potential, mobile hydraulics.

1. INTRODUCTION

The EU directive on the energy performance of buildings requires member states to set limits on the total global warming potential (GWP) of new buildings from 2030. The total life cycle GWP include emissions emitted during the construction phase of a building [1]. Already since July 2025, the Danish building regulations (BR18) include mandatory GWP limits for the combined emissions during transportation to and from a construction site (phase A4) and during construction and assembly (phase A5) [2]. BR18 requires the measurement and reporting of consumed energy for vehicles heavier than 1 ton, motivating the live monitoring of energy usage and energy optimization of construction equipment.

Using a wheel loader as an example vehicle, this paper shows how a static simulation model can be used to augment standard measurements to enable component level energy consumption calculations. The aggregated data can be used to fulfill regulations like BR18 while the individual data can be used for system efficiency optimization. This individual energy data can be shared using standardized interfaces like the Asset Administration Shell (AAS) [3] as tested in the research project Fluid 4.0 [4].

In the next section the wheel loader and the load cycle are introduced. A wheel loader enables the analysis of two common hydraulic functions: propel and cylinder-based work functions. Next the simulation model is introduced. It is based on quasistatic analysis of the individual components. Section 4 discusses the energy losses of individual components and highlights potential savings. Section 5 presents how the results of section 4 can be postprocessed to fulfill regulations and outlines how these values can be shared effectively using the AAS. Lastly, the results are evaluated and future steps discussed.

2. WHEEL LOADER DEMONSTRATOR

The test vehicle is a mid-sized wheel loader shown in **Figure 2.1**. It is equipped with sensors for pressures, rotational speeds, positions, control currents, temperature, and flows. However, not all measurements are required for the energy flow calculations. Notably the flow measurements which are not provided in standard applications are not required. During a Y-cycle, four hydraulic functions were investigated: the hydrostatic drivetrain, articulated steering, lifting of the boom through two parallel cylinders and tilting of the bucket.

Figure 2.1: Wheel loader used for testing.

2.1. Wheel Loader

A modified Paus RL 8.7 wheel loader with a weight of 6.5 tons is the test vehicle. It has three hydraulic circuits of which two are discussed in this paper. First, the hydrostatic drivetrain consists of a single motor and a single pump. Second, the work functions (WF) are driven by a single open circuit pump. The fan drive system is not discussed in this paper but also contributes to the load on the main engine.

The drivetrain consists of the variable displacement axial piston pump Danfoss H1P-078 and the variable bent-axis motor Danfoss H1B-110 connected to a Dana Spicer 367 gearbox. All measurements were collected in first gear. The investigation of this paper focuses on the hydraulic components. This means that losses in the gearbox and the engine are not considered. A simplified overview of the propel and work function hydraulic components can be seen in **Figure 2.2**. Load sensing, load holding, pilot, cooling and emergency functions are not shown and not considered in the simulation.

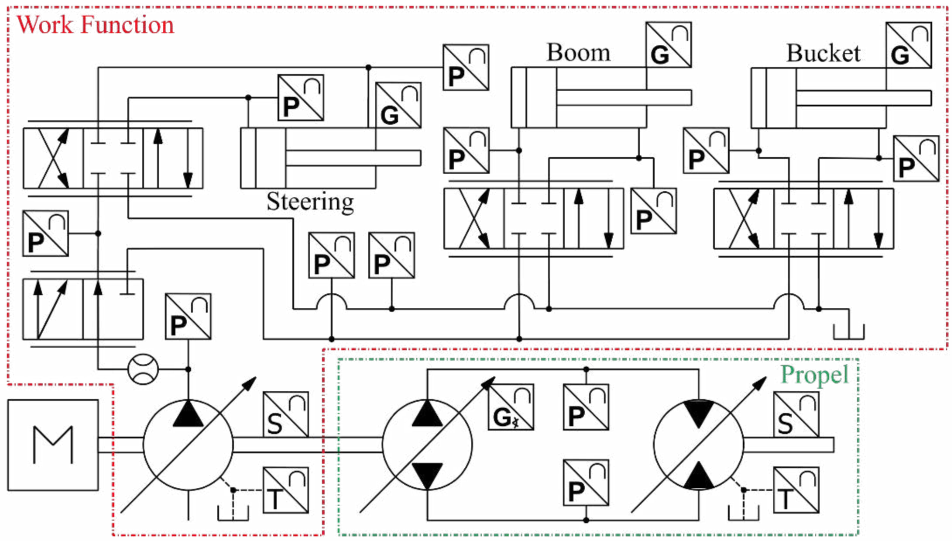

Figure 2.2: Overview of hydraulic circuit and measurements taken.

In the propel circuit the following quantities were measured: Pump and motor shaft speed, pump displacement angle, line pressures at motor and pump side, and motor drain temperature.

The open circuit hydraulics drives four work functions: articulated steering, boom lifting, bucket tilting, and auxiliary hydraulics. During testing, no auxiliary hydraulics were connected, leaving three hydraulic functions. All functions are driven by a single load sensing open circuit Danfoss S45-75 pump. The pump outflow is passed through a priority valve, giving priority to the steering function. A Danfoss OSPC250 steering unit controls the flow to the steering cylinder. Flow to the boom and bucket cylinders is controlled by two proportional Danfoss PVG valves. All returning flow from the steering unit and the proportional valves is filtered and cooled. The boom cylinders are equipped with a ride control unit. While the ride control unit was not actively used in any of the tests, the automatic system still precharged the accumulator for potential use.

Measurements were recorded with a sampling frequency of 500 Hz. The position of the cylinders was captured using draw-wire position sensors. Pressure was measured at the pump side of the steering unit and proportional valves, at both sides of all cylinders, and the pump outflow. The temperature was recorded in the pump case flow and after the cooler. Furthermore, the outflow of the open circuit pump, flow into the ride control unit and into the steering unit were measured.

2.2. Load Cycles

The Y-cycle was performed as shown in **Figure 2.3** on loose gravel. To start the cycle, the wheel loader is positioned with an empty bucket and raised boom at the drop-off pile on the right (1). Splitting the cycles at the drop-off ensures that the start and end states of the cycles are as similar as possible, because the boom is at a defined position. First, the wheel loader reverses and starts lowering the boom. The vehicle switches directions at point 2 and drives to the left pile (3). When reaching point 2, the boom might not be fully lowered yet. At point 1 the bucket is filled and the boom raised while driving in reverse to the initial turning point (4). The cycle ends by dropping the gravel at point 1. In total 8 cycles were recorded.

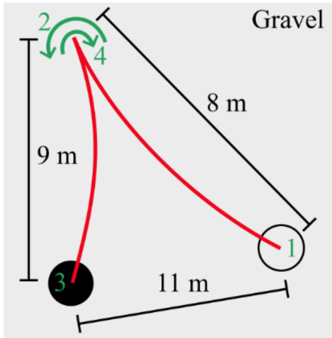

Figure 2.3: Wheel loader test cycle.

Figure 2.4 shows the vehicle speed and boom cylinder displacement with corresponding pressures during the test cycle. During the reverse driving from point 1 to 2, the propel delta pressure is negative during acceleration and positive while braking. After passing point 2 and driving forward, this relationship switches. Pressure during acceleration is now positive. While driving from 1 to 3, the boom is lowered. The boom pressure spikes when the wheel loader hits the gravel pile just before point 3. With a full shovel the boom pressure is higher and exhibits oscillation.

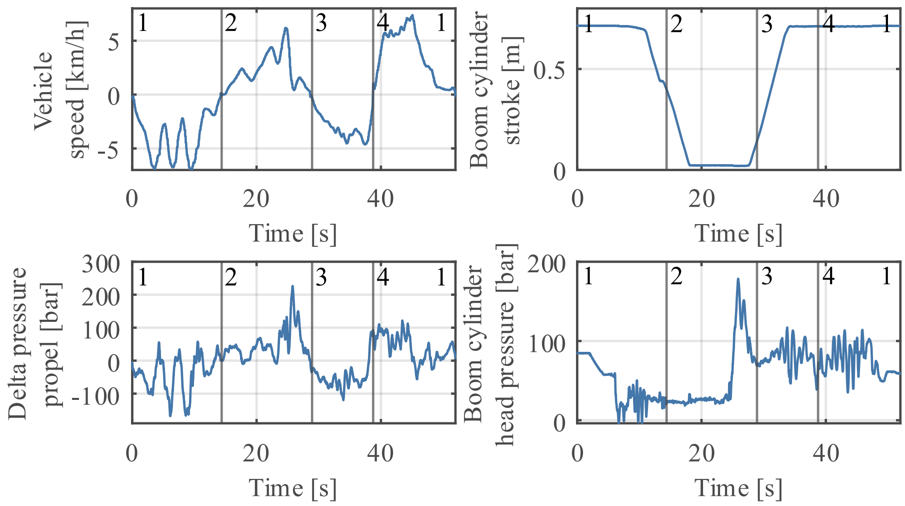

Figure 2.4: Measurement examples for test cycle.

3. SIMULATION MODEL

A quasistatic simulation is used to augment the measurement data and calculate the power flow through each component in every timestep. The simulation model is modular, allowing to swap measurements for simulation components and vice versa. Compared to an analysis only based on measurements, this approach allows replacing hard-to-measure hydraulic quantities like volumetric flow rates by simulation models. On the other hand, hard-to-simulate or unknown hydraulic components can be replaced with measurements. Compared to a full dynamic simulation, no complex environment needs to be simulated. In the following the overall simulation methodology as well as the component models and required external inputs are presented.

The main components of the hydrostatic system are modeled by a component model defining its hydraulic, mechanical, and electrical connections. Every component model defines linear and non-linear relationships between its connections. For example, a pressure relief valve model might define two equations:

1. The inflow is equal to the outflow as a linear equation.
2. The relationship between throughflow and pressure-drop as a non-linear equation through a look-up table.

If the relationship between throughflow and pressure drop is unknown, only the first equation can be defined. Instead of defining the second equation, pressure can be measured on both sides of the valve such that the system can still be solved.

To solve the complete system, the linear and non-linear equations of the individual component models are assembled into a system of linear and a system of non-linear equations using the hydraulic, mechanical, and electrical connections of the components. The system of linear equations is solved first and the solution substituted into the non-linear system. Next, the measurement values are substituted into the non-linear system, and the system is solved using a numerical solver. In postprocessing steps, the system solution is transferred to the individual component models and the power flow through each component is calculated. The modeling framework is implemented in MATLAB.

The level of detail of the component models depends on the available product knowledge and availability of measurement data. While a lot of information is known about the hydrostatic pumps and motor, less information is available for the valves and cylinders. In the following, first the models of the work function circuit and then of the propel circuit are presented.

The performance characteristics of the open circuit pump are known allowing a detailed model. The Polymod efficiency map based on [5] is used to define the non-linear relationship between pressure, shaft speed, displacement angle, temperature and flow. Due to the detailed model, no measurement of the displacement angle is necessary.

In contrast to the open circuit pump, the 4/3-valve performance characteristics are not known. The valves connections are modelled as generic pressure drops. Based on the valve control signal, flow continuity between the connected ports is ensured. Furthermore, the model ensures fluid flows from high to low pressure. The amount of fluid flow is determined by the connected cylinders.

Pressure and position measurements are available for all cylinders. The cylinder model is lossless. Speed, inflow, and outflow are calculated using the time derivative of the position. The cylinder force is computed using the differential cylinder area and the measured pressures.

The propel pump and motor are modelled analogous to the work function pump. Motor and pump shaft speed as well as both line pressures are measured. One more measurement is needed to specify the power flow through the drivetrain. As the control of the pump is equipped with an angle sensor, the displacement of the pump can be determined. Through the efficiency maps of pump and motor, the system flow and motor displacement are calculated by the model. As the flow through the system is based on the pump equations, the pump efficiency model and measurements specifying the evaluation point need to be accurate.

In summary, the simulation model calculates flow, torque and force based on pressure, control signals, pump angle, linear speed, and rotational speed measurements. In a postprocessing step power flow across the connections and power loss in each component are calculated. The presented model is not solvable for all measurement times. This is likely due to the violation of the quasistatic assumption of the simulation or errors in measurement as discussed in section 4.

To validate the simulation for the solvable states, the propel motor displacement and work function pump flow are used. Unlike in a real-world application, the flow rate of the work function pump was measured and is plotted along the simulation result on the right-hand side of **Figure 3.1**. The overall fit between measurement and simulation is good, but for certain time periods, for example around the 30 s mark, the simulation has an offset to the measured value.

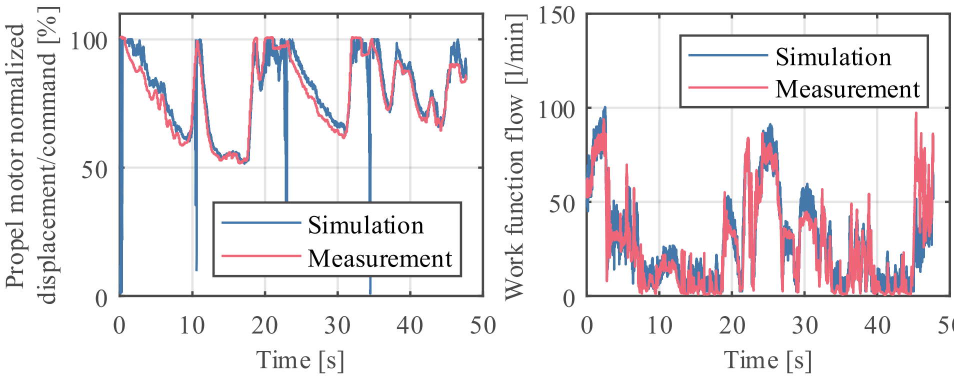

Figure 3.1: Comparison between simulation and measurement data.

No flow rate was measured in the propel hydraulic circuit. However, due to the mechanical feedback link in the motor control, the motor displacement correlates well to the motor control signal. Hence, the simulated normalized motor displacement is compared to the normalized motor displacement command on the left-hand side of Figure 3.1. Like in the work function circuit, the simulation matches the commanded value well most timesteps. However, around the times when the simulation is not solvable, the simulated displacement drops sharply. As the simulation failures are of short duration, the impact on results concerning a complete Y-cycle is small.

4. RESULTS

This section presents the results derived from augmenting the measurement data with the simulation model and the subsequent energy calculations. The Y-cycle described in section 2.2 was performed 8 times by a non-professional driver. The power flow between components, during different operating phases and differences between cycles are discussed. The analysis focuses on the main power flow, neglecting control flows, cooling flows, and dynamic effects. As the sample size is small and the data was gathered in a test setup and not during regular operations, the results are only illustrative.

First, the power flow through the hydraulic system is discussed. The Sankey diagram shown in **Figure 4.1** shows the power flow between the components during one particular Y-cycle. Red arrows mark the useful work performed by the boom, bucket, steering unit, and wheel relative to the absolute engine output power. Roughly half of the energy provided by the engine is used for the work functions, the other half is used for the propel application. About a third of the energy provided by the engine is turned into useful work. In the median cycle 28 % are used at the wheel, 4 % at the boom, and about 1 % for steering and bucket tilting.

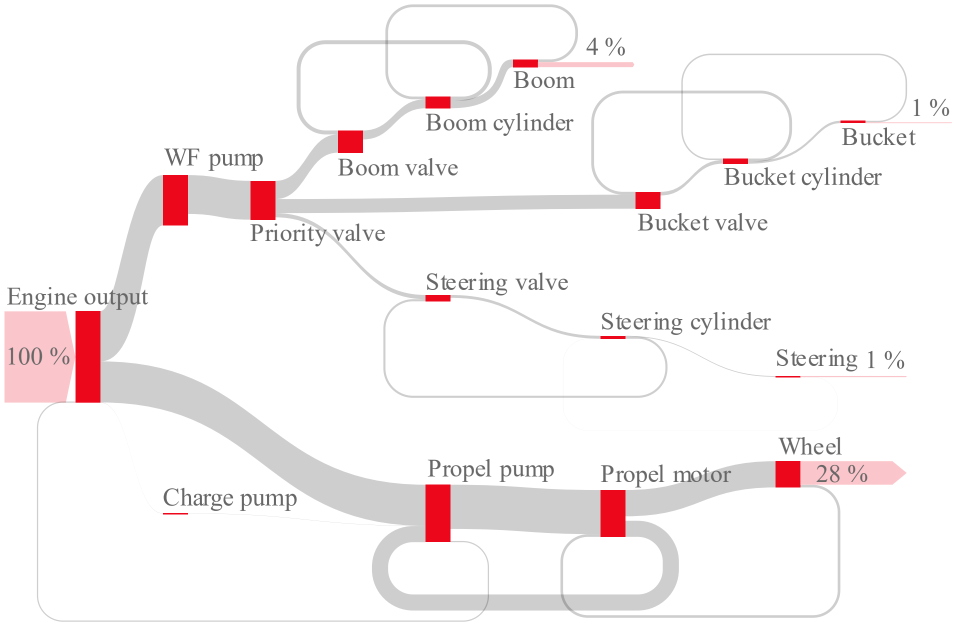

Figure 4.1: Energy flow during 1 Y-cycle. Red arrows mark hydraulic system energy inflow and outflow.

In the work function system, the priority valve splits the work function flow between the cylinders and the steering function. The losses in the priority valve are minor. The highest relative losses are in the throttling valves to the cylinders. As Figure 4.1 shows the energy flow across a complete cycle, it includes raising and lowering of the boom. During raising unnecessary losses occur in the valve as the pressure level between the cylinders differ. While lowering, all potential energy from boom and bucket is converted to heat. A hydraulic circuit which allows for energy recovery, could recover energy during lowering. Roughly 42 to 76 % of the energy required to move the bucket and 26 to 36 % for the boom are provided back at the cylinders during cylinder retraction. The large spread in recoverable energy for the bucket highlights the influence of vehicle operation on energy saving potential.

The propel system has a median efficiency of roughly 64 % engine to wheel. Only about 8 % of the energy provided to the wheel is returned to the motor during braking. The rest of the energy is lost to friction, especially due to the loose gravel ground. A comparatively large energy flow from the propel motor to the propel pump can be observed due to the low pressure return flow at around 22 bar.

All results are based on measurements with a sampling rate of 500 Hz. All calculations have been repeated with lower sampling rates. With the 500 Hz computations as a baseline, the relative error stays below 1 % for sampling rates up to 20 Hz. For the same sampling rate, the relative error in the work function components is larger than for the propel components. This means, sensors capturing the work function hydraulics need to have higher sampling rates to achieve the same accuracy level.

For a few timesteps, no solution within the physical limits of the components could be found. In these cases adjacent solutions were linearly interpolated. The most common cause for unsolvable system states is the propel motor on maximum displacement not being able to consume all flow produced by the pump. Likely reasons for the surplus of flow on motor side are the neglect of control losses for the propel motor, violation of the quasistatic assumption and measurement errors. The issues might be alleviated by smoothing the measurements before processing in the simulation model.

Figure 4.2 gives an overview of the energy outflow of the system while the same Y-cycle was performed 8 times. The top 4 energy sinks (red borders in Figure 4.2) are the useful work performed for the steering, bucket, boom and propel function. All other items are losses in the hydraulic circuit. While the energy provided by the engine to the work function and propel circuit is similar (see. Figure 4.1), more work is being done by the propel circuit. This is caused by the efficiency of the propel circuit being larger than that of the work function circuit. While the efficiency of the rotating units is larger than the efficiency of the valves, the absolute energy loss is comparable, because the rotating units handle a larger energy flow.

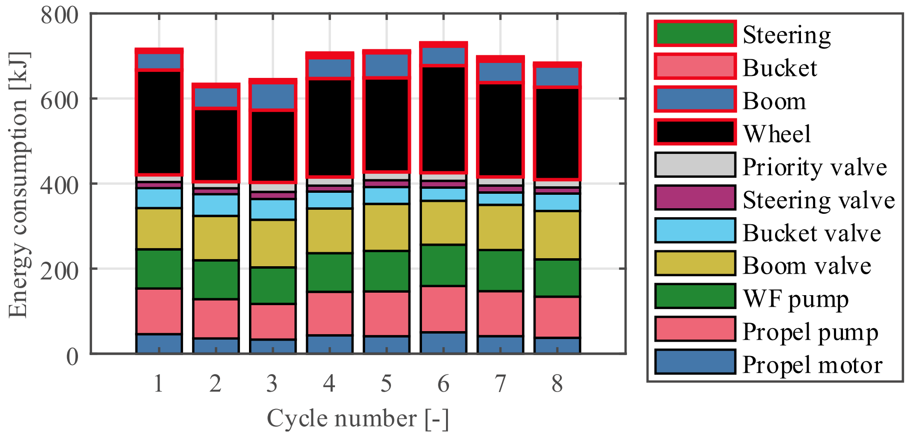

Figure 4.2: Work performed (red border) and energy loss of individual components.

The median energy used in a single Y-cycle is 700 kJ. In all cycles the same work was performed by the same operator. The large spread of total energy consumed, 14 % of the median, highlights the importance of repeated field measurements. To acquire exact energy consumption and emission values, measurements as presented in this paper are required. Accurate knowledge of energy consumption is the basis for GWP calculations in the next section. Furthermore, the energy data can be shared directly via the AAS as demonstrated in the Fluid 4.0 research project and explained in the next section.

5. Emission Calculation and Sharing

The energy flow data presented in section 4 is the basis for computing key climate emission indicators. An overall GWP value for the wheel loader is calculated based on the total energy output of the engine and then attributed to the components of the hydraulic system. The total GWP potential can be used to fulfill building regulations like BR18. Individual GWP of the components can be used to calculate the lifetime GWP of individual products. To share the GWP information along the value chain, the standardized interface of the AAS is used. This facilitates the further automatic processing of the emission information into Life Cycle Assessments (LCAs) and other documents required to meet regulations.

Building regulations like BR18 not only stipulate overall emission limits for materials and the use phase of a building, but also specific limits for transportation to and from a construction site (phase A4) and during construction and assembly (phase A5). While the calculations for phase A4 can be performed based on the distance driven by trucks, the energy consumed during construction and assembly needs to be measured directly. For diesel fueled machines, this can be achieved by measuring the fuel consumption or using the engine's specific fuel density and engine energy output calculated in section 4. By using time stamps, the latter approach can be used to assign emissions to the corresponding projects, when a construction machine is performing work for multiple projects on one tank filling. By multiplying the engines' specific fuel consumption of 221 g/kWh and the GWP (including life-cycle emissions) of diesel of 4.13 kgCO_2e/kg [2] with the engine's power output, the median GWP for one Y-cycle is calculated to 178 gCO_2e. Note that the GWP of diesel varies with the calculation scope determined by the regulation. The value provided by BR18 not only includes the direct effects of diesel combustion, but also emissions generated during sourcing and transportation.

Following the same calculations, the GWP for individual components may be calculated. The GWP for individual components may be used as a data point in the components LCAs. Due to the versatility in use of hydraulic components and the strong impact on energy losses, only real-world measurements can provide an accurate value for the GWP of a component in a specific system. If, for example, the same valve is used in a work function system with accumulator and energy recovery, less energy loss in the valves during lowering is expected. While the proposed method provides an accurate GWP value for a component in a specific system and use case, it is difficult to compare it with the GWP of other products without testing them under the same conditions. On the other hand, a GWP value based on testing defined operating points does not represent the real GWP value of a component, but it ensures that GWP values between similar products are easily comparable.

The calculated emission data is needed by a variety of parties along the value chain. In the example of a rented wheel loader working on a building, the raw emission data might be used by the construction site management, the rental company, vehicle manufacturer, and hydraulic component manufacturers. While the construction site management and rental company are primarily interested in aggregated vehicle level data, the vehicle and component manufacturers have an interest in emissions of particular components. Field data for components ensures that emission reporting is based on real life and thus actual emissions are tracked and can be reduced over time.

To facilitate the sharing of emission data with the different parties in varying granularity, a standardized exchange format is needed. A digital machine-readable format is preferred, because the emission data needs to be aggregated and processed at the different parties before being ready for reporting. One exchange format which is gaining traction in the fluid power industry is the AAS [6]. The AAS framework specifies the technical aspects of data exchange and the data content on a semantic and structural level. The content level structure is described in submodules. For example, a submodule “Energy Monitoring”, facilitating sharing of component level energy data, is currently developed in the research project Fluid 4.0 [4]. The prototype of the submodule Energy Monitoring was used to provide the energy data of this paper in a standardized format to the Fluid 4.0 project partners.

Multiple submodules holding carbon footprint data are already released or under review. The submodel Carbon Footprint can be used to share carbon footprints which were calculated according to ISO 14067 or similar standards [7]. However, two further submodules related to product emission data are in review by the IDTA: Digital Battery Passport – Part 3: Product Carbon Footprint and Product Related Environmental Data [8]. Multiple submodules holding the same or similar data hinders efficient automatic processing of the information within. Ideally every piece of information would have a well-defined unique place inside the AAS. In the future, it is important to consolidate overlapping submodules to create submodules which are general enough to apply to a wide range of assets while providing a unique place for specific information.

6. CONCLUSION AND OUTLOOK

Using a wheel loader as a test machine, this paper demonstrates how standard measurement data can be augmented using a static simulation model to analyze energy flow within a hydraulic system and compute global warming potential (GWP) of vehicle operation to fulfill emission regulations of construction sites. The information about energy flow between components is helpful for system optimization and emission reporting of individual components. Furthermore, the energy and emission information can be shared with parties along the value chain using the Asset Administration Shell (AAS) as a standardized format.

The energy loss of hydraulic components and thus the overall system efficiency is strongly dependent on the load cycle for each component. The individual load cycles depend not only on the machine load cycle, but also on the operator. This makes energy calculation based purely on system simulation difficult, as defining realistic load conditions is challenging. On the other hand, measuring all flow and pressure quantities in a real hydraulic system to determine energy losses, is costly and time consuming. The methodology outlined in this paper reduces the need for a complex sensor setup by augmenting the test data using static simulation models for the individual components. The resulting energy flows show large variations of 14 % in energy consumption between cycles of the same task, highlighting the need for real world measurements to achieve accurate results. Accurate live data is required to fulfill emission limits targeting the use phase of a machine like the Danish building regulation BR18. For planning purposes, it needs to be investigated if the GWP results can be generalized to different drivers, cycles or even machines of different sizes using a larger data set.

To facilitate accurate emission reporting for all stakeholders, emission data needs to be communicated along the value chain. An AAS allows standardized machine-readable communication of the emission data to various parties. Next to emission data, per component energy data can be shared to facilitate system optimization and lifetime load calculations.

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Biographies

Moritz Neltner received a bachelor’s degree in mechanical engineering in 2020 and a master’s degree in theoretical mechanical engineering in 2022 from Hamburg University of Technology. He received a master’s degree in technology management from the Northern Institute of Technology Management in 2023. Since 2023 he works at Danfoss Power Solutions as a simulation engineer focusing on system simulation, data automation, control, and condition monitoring for mobile hydraulics.

Dr. Robert Rahmfeld is the Senior Director Engineering for Hydrostatics at Danfoss Power Solutions, being technically responsible for hydrostatic axial piston units. He is with Danfoss over 20 years, holds several patents, and is author or co-author of more than 60 scientific journal and conference papers. Dr. Rahmfeld completed his PhD on new displacement controlled hydraulic linear actuators at the Technical University of Hamburg-Harburg in 2002 under supervision of Professor Monika Ivantysynova, and his MSc in mechanical engineering at Duisburg University in 1996. He was also holding a postdoc position in fluid power for 2 years at the Technical University of Hamburg-Harburg and Purdue University, Indiana, USA. Dr. Rahmfeld represents Danfoss within the VDMA fluid power board and is also the chairman of the corresponding fluid power research fund with more than 60 member companies. He was awarded in 2024 by Purdue University with the *Monika Ivantysynova Medal* for technology advancements of hydrostatic units and their controls, and for leadership in fostering industry - academic initiatives to promote fluid power.

Senior Director **Dr. Andreas Schumacher** is responsible for Sustainability and Product Compliance for the complete Danfoss Power Solutions segment. He joined Danfoss in 2007 as a simulation engineer after his PhD on mobile machinery tire and driving dynamics simulations at the Technical University of Braunschweig under the supervision of Professor H.-H. Harms. The career development over the nearly 20 years in Danfoss increased his responsibilities and also changed from Engineering to the current role. Dr. Schumacher is also author and co-author of over 30 journal and conference papers as well as presentations. As part of his current role, he is representing Danfoss Power Solutions externally in the field of mainly Sustainability in regulatory, scientific/research and business contexts and further publications like publicly available podcasts (e.g. on Spotify).