MODEL BASED EFFICIENCY ANYLYSIS OF MOBILE HYDRAULIC MACHINERY
On The Example of Material Handling Machines

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Abstract. Multi domain simulation is a powerful tool to compute the energy- or fuel saving potentials of drive systems compared to alternative drive concepts. For a practice-oriented evaluation of energy efficiency, typical cycle data of the target application with respect to the process are necessary. A comparative analysis of different efficiency values is conducted based on a holistic machine model and cycle data derived from measurements and standards.

Keywords: Material Handling Excavator, Energy Efficiency, Simulation, Reference Cycle

INTRODUCTION

There are many characteristic values describing the energy and exergy balance of systems. Exergy is the maximum fraction of work a system is capable of delivering to an existing environment. Therefore, it represents the amount of energy, which can be converted into any other forms of energy. Energy consumption or more specific exergy conversion expresses the amount of energy used during operation [7]. [6] distinguishes between effectiveness and efficiency. While "Effectiveness [is seen as] doing the right things" „Efficiency is concerned with doing things right". Determining effectiveness requires a defined goal at first. If this goal is achieved, the procedure is considered effective, irrespective of the used effort or resources. Effectiveness is therefore the ratio between the achieved goal and the defined goal using all means. If the goal defined by the effectiveness has been achieved, efficiency can be assessed. The fewer resources or effort required to achieve the goal, the more efficient the goal is achieved. The current efficiency-value η_{cur} is a function of time. It is determined by the ratio of the output power P_{out} to the input power P_{in}. The input power corresponds to the sum of output power P_{out} and power loss P_{loss}.

$$\eta_{cur} = \frac{P_{out}}{P_{in}} \tag{1}$$

Since the current η_{cur} power ratio is a time-dependent variable, high and low efficiency phases can be detected when evaluating time-based plots. The current efficiency thus allows for comparison of efficiency characteristics of different drive systems during the execution of the working cycles. Due to the changing power requirements and the high dependence on the operating point, it is often referred to the average efficiency η_{avg}. An average value over time is calculated in [4]. The integral of the current efficiency η_{cur} (t_0, t_1) is divided by the cycle duration time T:

$$\eta_{avg} = \frac{1}{T}\int_{t_0}^{t_1} \eta_{cur}(t)dt \tag{2}$$

Similarly, the average efficiency η_{avg} can be calculated from the ratio of the output work W_{out} and the work supplied W_{sup}.

$$\eta_{avg} = \frac{W_{out}}{W_{out} + W_{loss}} \tag{3}$$

Regarding the above-described definition of efficiency, the current and average efficiencies do not consider the utilization of resources to solve the task. Here the degree of energy utilization ε describes the share of energy which is used solely for performing the work task. According to [18], a utilization factor is the quotient of the target energy expended in a given time period and the total energy supplied. In the period under consideration, all

deceleration , standstill, idle and start-up times are included, see also [9]. If one sets the balance limits outside the machine system, a process utilization degree can be derived. For this purpose, the difference between the required energy for performing the work task and the necessary energy of the same machine operation without process interaction is related to the input energy.

$$\varepsilon=\frac{E_{input}-W_{out,\,loadfree}}{E_{input}}=\frac{\int P_{input}dt-\int P_{out,\,loadfree}dt}{\int P_{input}dt} \tag{4}$$

During loading operations of excavators or wheel loaders, the productivity can be assessed by using a quotient of the quantity of the loaded material and fuel consumption or the time required. Likewise to parcels or pallets, the bucket or bucket capacity, stated as volume or corresponding to the load material density as a mass, can also be referred to transport units [6].

STATE OF THE ART

Due to the great heterogeneity of mobile machinery, it is very difficult to define specific methods of energy efficiency evaluation. Furthermore, the machine operators have a great influence on the machine's energy consumption (construction method, chosen machine size, machine age). However, today there are several methods and guidelines for evaluation of fuel consumption for different types of mobile machines. VDI-directive 2198 applies to **industrial fork lift trucks**. Working cycles are defined to determine the fuel consumption of different machines. A defined number of work cycles is to be carried out within 1 h. The driving speed must be adjusted accordingly. The lifting height (2 m) and the distance between the loading points is adjustable for different types of machines. [17]. Due to the predefined handling performance, the procedure is considered to be less practical, since the cycle seems to be very slow. In case of the so-called TO-cycle, the stackers are moved at their power limit in order to determine the turnover performance with respect to a work shift. At the same time, the average consumption of one hour and one hundred pallets is also determined [6]. A similar method was developed by Linde Material Handling GmbH. Within the working cycle a defined number of pallet cages with a fixed weight has to be loaded and unloaded off a truck. The cycle should be completed as fast as possible. In this manner realistic values of turnover performance and energy consumption can be determined.
The **DLG Powermix** [1] is a test method for tractors developed by the German Agricultural Society (DLG). Due to changing working conditions, former standard in-field cycle measurements were found to be inaccurate. Based on real measurement data, the DLG Powermix defines 11 working cycles covering the complete working range of a tractor (plowing, sowing, harvesting under full load and partial load conditions). The values of hydraulic output power, traction force and PTO-shaft- torque are predetermined over time. The load cycles may be adjusted to the installed engine power of the tractor via a scaling factor. To ensure a minimum process quality, the difference between velocity demand value and actual velocity value (velocity error) is to be kept low.
Japan Construction Mechanization Association (JCMA) has issued a test specifications for the fuel consumption of construction machines [11]. For an excavator work task a simulated trench-digging-cycle is demanded. The material is dumped into a truck after a 90°swing. There is no contact between the blade and the ground so that the soil conditions and working loads are not taken into account [19]. Depending on the machine's bucket size, specific cycle parameters are defined. The advantage of this approach lies in a standardized and comparable evaluation method for several characteristic operating tasks of machines. However, by avoiding blade-to-soil interaction, the machine is operated only in partial-load operation. In addition, the test drivers have an influence on the resulting working cycles. The test methodology has not yet been successfully introduced in the Europe. **Liebherr** uses a standard test for wheel loaders to determine the number of loading cycles, which can be carried out with 5 l of diesel[13]. Within a 35 s loading cycle the material is loaded, transported and dumped in a distance of 20 m. The unloading height shall be carried out at 2.5 m. The tasks are repeated until the fuel-reservoir (external measuring canister) is depleted. The measured number of load cycles is used to derive fuel consumption per hour as well as specific fuel consumption per tons of material. Setting the cycle time to a constant value reduces the driver's influence. The **NRTC** (non- road transient cycle) test is a transient duty cycle for non-road diesel engines developed by the US EPA in cooperation with the authorities of the Europe (EU).

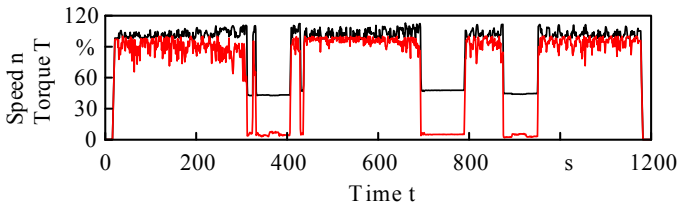


FIGURE 1. Normalized Speed and Torque over time in NRTC cycle

The test is internationally used for emission certification/type approval of non-road engines. Several emission

standards for non-road engines, including the EU Stage III/IV regulation, the US EPA Tier 4 rule as well as Japanese 2011/13 regulations, require NRTC tests. The engines are operated with a dynamic speed and torque profile with a total duration of 1238 s. The NRTC is run twice, with a cold and a hot start, with a 20-minute soak period between the tests, see figure 1.

A Cycle-based efficiency analysis using simulation has been conducted by [10], [21] and [20] among others. The energy distribution in relation to hydraulic pump power or mechanical shaft power was calculated at a given handling capacity. *DEITERS* developed a methodology for the standardization of measured load cycles in order to be able to evaluate the efficiency of mobile machines using simulation of representative working cycle. The investigation is conducted on a wheel loaders' short loading cycle. With the standardized load-cycle, two different drive concepts are evaluated based on the efficiency profile and the mean efficiency [4].

FLECZOREK shows that simulation-based efficiency analysis is only possible in combination with working condition profiles. They enable the identification of the operating points with the highest power losses on the one hand and with the highest energy losses on the other hand. For example, an operating point with high power losses but a small duration time might cause relatively low energy losses. Regarding drive systems with different functions and the corresponding power requirements, a high functional degree of efficiency is not equal to low energy losses and vice versa. Therefore, the working condition profiles are the key factor to benchmark mobile machine drives based on total energy losses during machine life time [6].

The human operator has an significant influence on the drive technologies' efficiency of mobile machinery. He directly controls the construction machine's movement. Hence there are significant interactions regarding the usage of engine power or the operating point of hydraulic components depending on the operators' individual behavior and skills [10]. The handling performance and acceleration capability are also influenced by the driver type. For this purpose, operator models are developed and used to map the human control behavior taking into account the machine and ambient conditions [5]. In order to evaluate the efficiency by means of simulation, dynamic machine models as well as environmental models are necessary. In [16] the methodology presented is applied to a wheeled excavator. To ensure a realistic power demand, a rule-based operator model is developed. The operation rules of excavation are implemented into the model. This enables the generation of realistic, machine-specific working cycles. Using the example of a 90° -cycle it is proposed to define standard cycles for the evaluation by defining the operation rules. The results show that the developed methodology is suitable to perform a systematic optimization of power train efficiency. *MIETH* on the other hand postulates, that the machine operator cannot be described in a formal way covering all of his skills and properties. Reasons are the diversity of human individuals, the ability of humans to permanently adapt their behavior to new and unknown situations as well as enhancing and honing their skills through learning and experience [12].

In summary, it can be stated that energy efficiency becomes more and more important for the development of mobile working machines. However, a standardized approach for the efficiency evaluation of mobile machines does not exist up to now. Besides missing standards for test procedures, the variety of machine types and sizes complicates the development of uniform solutions.

ANALYSIS AND MODELING OF THE REFERENCE MACHINE

Industrial excavators are used as working machines e.g. on wood or scrap sites and harbors (see figure 2). On scrap sites, they mainly handle car chassis and light scrap parts. They load and unload transport vehicles or presses. High annual operating times of up to 4000h are possible. When handling bulk material with clam shell buckets, a loading cycle takes about 25-36s, so that 2000 to 2200 loading cycles per day are possible. Therefore, energy efficiency is a key topic for this type of energy intensive applications [2].

LH 40 Industry Litronic	
Operating Weight	36.400 – 38.700 kg
Eingine	(Stage IV) 155 kW
System Performance	220 kW

FIGURE 2. Liebherr Material handling excavator LH40 [Source: Liebherr]

Material handling excavators show a cyclic movement characteristic. The boom cylinder, stick cylinder and slew drive are the main hydraulic consumers. During operation, the kinematic conditions vary within certain limits, see figure 3. These variations result from loading requirements, machine limitations and operator behavior. For a model-based evaluation of energy efficiency, the selection of a representative loading cycle is crucial, since scattering input data result in false consumption values.

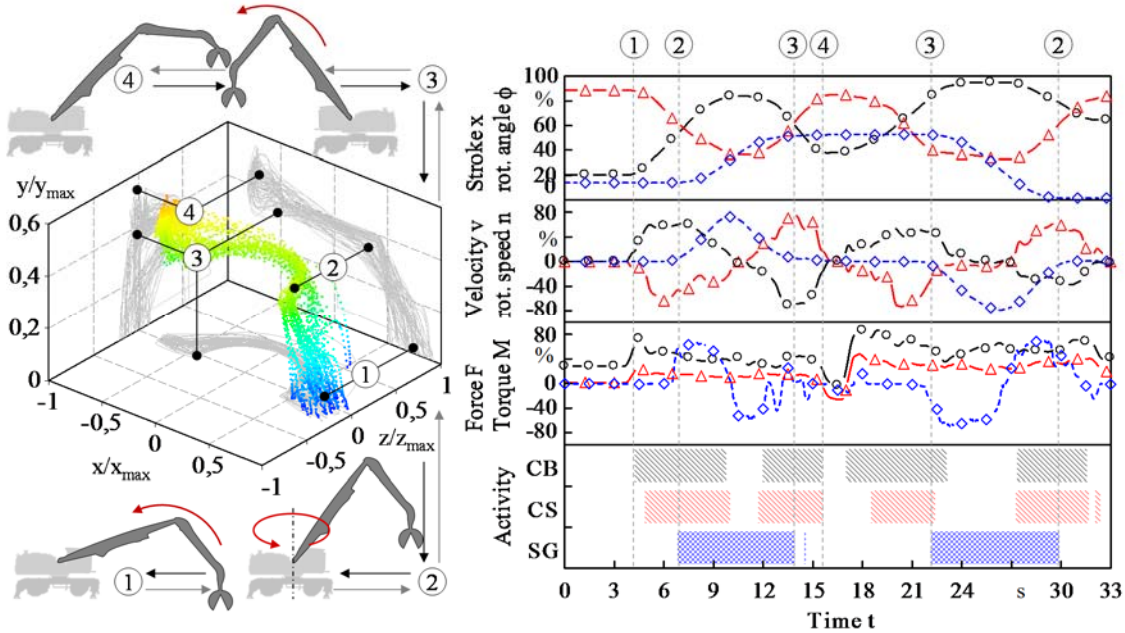
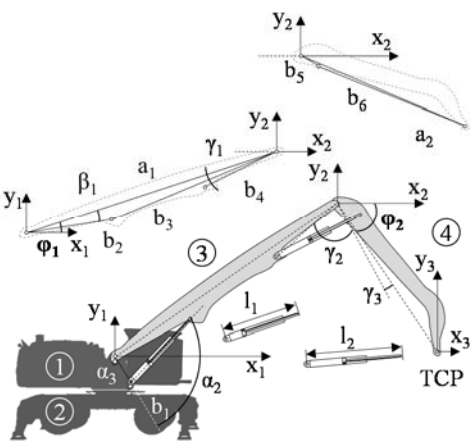


FIGURE 3. Working cycle characteristic

The working cycle may be divided in several phases. After picking up the bulk material (1), the operator lifts the working equipment (2) from the pile. In addition, the attachment's center of gravity is moving closer to the rotational axis. It decreases the inertia before starting to swing of the upper carriage (3). Following the rotating phase, the working tools are positioned directly above the silo's opening (4). To release the bulk material the clamshell cylinder is activated. All the other consumers are inactive at this point. The return movement starts by swinging back the upper carriage (3). This process takes place faster than the preceding one, since it is free of load. In addition, the consumers are operating simultaneously. After rotating back to the pile the next cycle (2) is prepared by the positioning of the working equipment (1).

With the help of the geometrical relations from figure 4, equation (1) is used for computating the rotation angle φ_1. The stick's motion is linked to the stroke of the stick cylinder along with l_2. Equation (2) prescribes rotation angle φ_2. The position of the tool center point (TCP) therefore depends on the variable rotation angles and the geometric shape of boom and stick. Thus, the exact location of the tool center point (TCP) can be determined by equation (3).



$$\varphi_1 = \arccos\left(\frac{b_1^2 + b_2^2 - z_1^2}{2 \cdot b_1 \cdot b_2}\right) - \alpha_3 + \beta_1 \quad (5)$$

$$\varphi_2 = \varphi_1 + \gamma_1 + \arccos\left(\frac{b_4^2 + b_5^2 - z_2^2}{2 \cdot b_4 \cdot b_5}\right) + \gamma_3 - 180° \quad (6)$$

$$\overrightarrow{TCP} = \begin{pmatrix} x_{TCP} \\ y_{TCP} \end{pmatrix} = \begin{pmatrix} a_1 \cdot \cos(\varphi_1) + a_2 \cdot \cos(\varphi_2) \\ a_1 \cdot \sin(\varphi_1) + a_2 \cdot \sin(\varphi_2) - l_G \end{pmatrix} \quad (7)$$

FIGURE 4. Kinematics Description of Working Attachment

The load-sensing system with flow sharing characteristic consists of two essential hardware elements. The first is the load-sensing pump regulator, which utilizes the highest load pressure as feedback signal, for a closed loop hydraulic-mechanical control circuit. The control loop set-point is a target pressure difference defined by a

preloaded spring in the pump regulator. By manipulating the main spool displacement, the load pressure is passed through to the load-sensing pump controller. The pump delivers as much volume flow as necessary to maintain the desired pressure difference in the system. The second core element is the secondary pressure compensator. By comparing the highest load pressure with the downstream pressure behind the metering orifice, the pressure compensator therefore controls the pressure drop over the main control edge. As a result, all main spool pressure drops of each section have the same value. The pressure compensator of the load-leading consumer is completely open and has nearly no throttling function. The combination of both measures ensures that the actuators' drive speed is only dependent on the main spool displacement of the respective valve section, see figure 5.

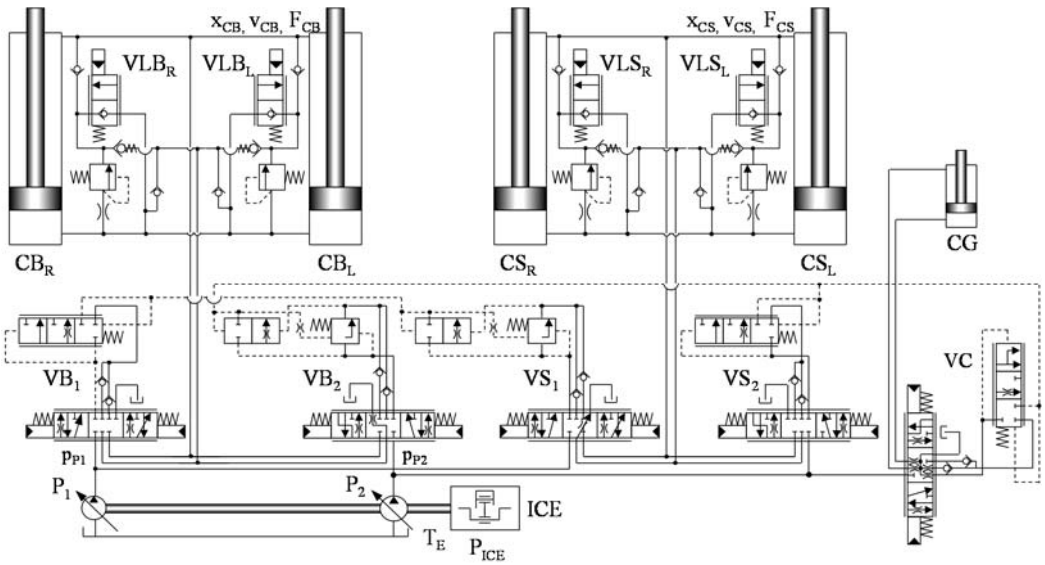


FIGURE 5. Simplified representation of the material handling excavator's hydraulic system

The use of lowering valves (VLS_i) allows retracting the stick and boom cylinders only by gravitational force and without the need for a pump activation. The piston-side flow is discharged and supports the cylinder during its lowering movement. The required filling volume on the rod side of the cylinder is directly fed back from the tank line. A closed-loop hydrostatic transmission (not shown), consisting of a variable displacement pump and a fixed displacement bent axis motor, drives the swing. The pump's pivoting angle determines the rotational speed of the upper carriage. Especially during braking, the drive's pressure-flow-coupling enables recovering kinetic energy. When the joystick is released the pilot-valves of the pumps' actuating system reduce the backward pivoting of the pump by throttling the control chambers' cylinder oil flow. As a result, the pressure sides change and shift the pump into motor operation. The braking energy of the upper carriage is converted into mechanical energy at the pumps' gearbox. In order to verify the model design and to validate the subsystem parameterization in the overall assembly, measurements of the hydraulic and mechanical state variables are compared with simulation results. In figure 6 left hand side the cylinder strokes (x_{CB}, x_{CS}) as well as their time derivatives (v_{CB}, v_{CS}) are illustrated.

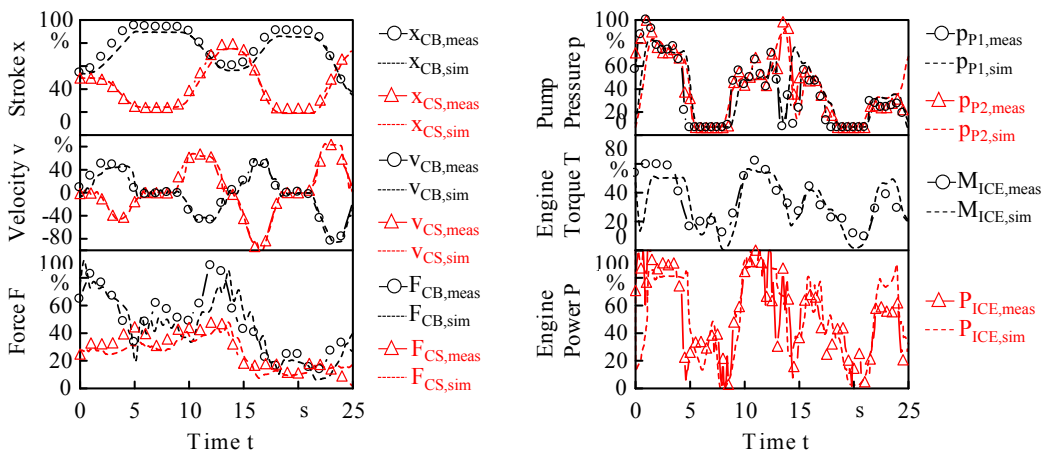


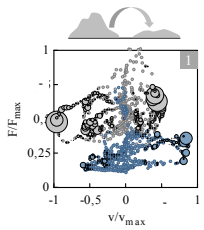
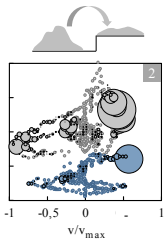
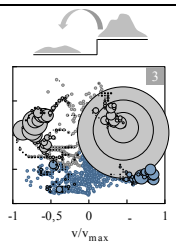
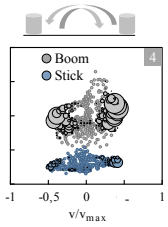
FIGURE 6. Comparison between measurement and simulation results

As validation criterion, the computed cylinder forces (F_{CB}. F_{CS}), pump pressures (p_{P1}, p_{P2}), engine torque and power (M_{ICE}, P_{ICE}) are compared with measurements. There is a very good correlation between simulation and testing results. The pump pressures (p_{P1}, p_{P2}) show some deviations at 14 s when the working equipment comes into contact with the ground. The entire weight of the working equipment is held by the ground and thus the load side is relieved. In the simulation, this ground contact does not take place for numerical reasons that leads to a higher remaining pump pressure level. The resulting effect on the power balance is negligible, since little volume flow is provided at this point. Bulk material with an average weight of approx. 2800 kg/cycle serves as the standard material, which is defined to be handled in all simulations. A superordinate controller calculates the control signals for the hydraulic subsystem.

EFFICIENCY ANALYSIS

The energy efficiency of the material handling excavator is evaluated according to typical application scenarios. The base line of comparison are both full- and partial-load working cycles, which result in different performance requirements and slewing angles. The resulting operating point distribution of force and velocity for boom and stick cylinders are shown in Table 1. The operating points are weighted using the normalized energy quantities at the respective operating point. The product of force, speed and cumulative dwell time over several cycles results in energy[1]. The size of the radii scales with the amount of the normalized energy share. It is obvious that the different working tasks have similar working point distributions, but differ in terms of energy demand. Thus, for prediction of realistic consumption data, a combination of proposed working tasks has to be taken into consideration. For the sake of simplicity all following investigation are conducted on the example of working task 1.

TABLE 1. Working task description

Task 1	Task 2	Task 3	Task 4
			
• Pick up material at ground level • 90 °/180 ° swing, Approach attachment to discharge position • Drop material into Silo at approx. 6 m height	• Pick up material at a depth of approx. 2.5 m • 90 °/180 ° swing, Approach attachment to discharge position • Drop material into Silo at approx. 6 m height	• Picking up material at elevated position (heap) • 90 °/180 ° swing, Approach attachment to discharge position • Dispose gripper over imaginary ship loader	• Pick up reference weight 1 with gripper • Deposit weight at marked place 1, • 90 ° swing, Pick up reference weight 2 • Deposit weight at marked place 2 • Permute weight positions crosswise

For a model-based evaluation of energy efficiency, the selection of a representative loading cycle (of each work-task) is crucial, since scattering input data result in false consumption data. The variance of the motion sequences, see figure 3, reflects various environmental influences (e.g. working process, operator characteristic). The set of similar (but never identical) space curves represents the characteristic cycles, from which the simulation input data (motion boundary conditions) for the actuators' partial motions have to be derived. If the driver's influence on the working cycle is low, the simulation of complete working cycles can be performed by applying fixed reference cycles. All systems are then faced with the same power demand [16]. One direct approach to generate reproducible energetic characteristics can be obtained by using complete measurement campaigns (operating cycles). In figure 7 a) the measured time history for a complete working task is shown. Here working task 1 is repeated 30 times. The mean cycle time is 25.9 s with a standard deviation of 1.2 s (figure 7 b)). The spread of the cycle times is mainly caused by different distances of loading and dropping points throughout the working process. All tests were conducted by skilled operators, who are able to utilize the machine power capacity in an optimal way. Furthermore, the filling degree of the clam-shell-bucket with loose material is very homogeneous.

[1] Since the state variables are subject to random oscillations, a classifying method according to [DIN 45667] can be used, which calculates the retention times of operating points within class boundaries.

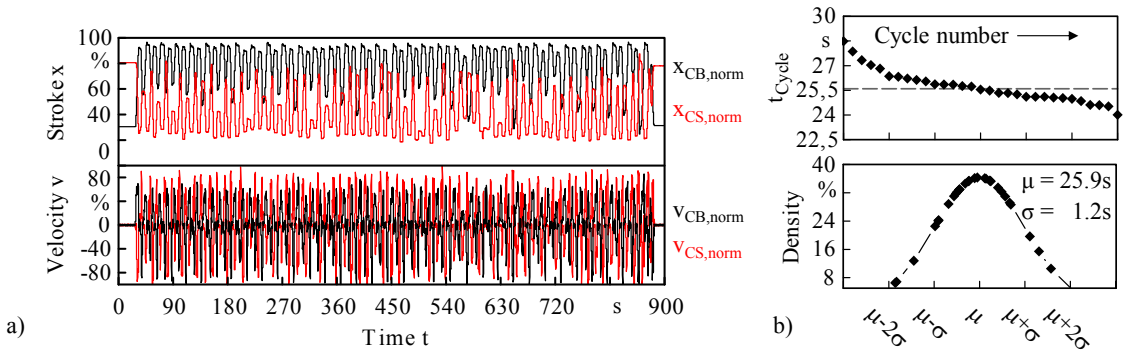


FIGURE 7. a) Time history for a whole working cycle (~30 single cycles) b) Cycle time distribution

There is a high calculation effort for the very long simulation periods as well as the linearly increasing memory requirements for the recording of the time histories of the state variables. In order to reduce the computational effort, there are a number of possibilities. All of them simplify the motion sequences:

(1) Standardized cycle [4]
(2) Equivalent reference cycles

Standardized cycle. By means of the measured cycle data, a single representative comparison cycle is created based on the method presented in [4]. The measured cycles are divided into distinctive phases, with reference towards characteristic speed traces (zero-crossings, maximum points, …). Different from the method in literature, in which only one subsystem (traction drive) was considered, there are several active consumers working in parallel for a typical excavator application. Therefore, the approach has to be extended. Phase boundaries are introduced when the drives significantly change their state of motion (e.g., boom/stick starting movement). The sections are synchronized according to [4]. The working step of the distance adjustment differs from the above-described procedure. An average duration for each cycle phase is determined, to which all phases are normalized respectively. Thus, the sections are synchronized by compressing or stretching the motion profiles. A compensating factor *K* addressing the deviations in the traveled distance compared to the averaged track is introduced.

$$K_i = \frac{\Delta s_{i,orig}(t_1)}{\Delta s_{i,sync}(t_1)} = \frac{\Delta s_{i,orig}(t_1)}{\int_{t_0}^{t_1} v_{i,sync}(t)dt} \tag{8}$$

As result, there are 30 cycles normalized to the same cycle time. From this set , the median is calculated for each consumer. The superposition of the velocity inputs represents the standard cycle. Calculating the integral of the velocity sequences determines the cylinder-strokes with the average starting point s_0.

$$s_i(t) = \int v_i(t)dt = s_i(t) + \bar{s}_{0,i} \tag{9}$$

Figure 8 a) depicts the resulting curves for boom and stick velocity.

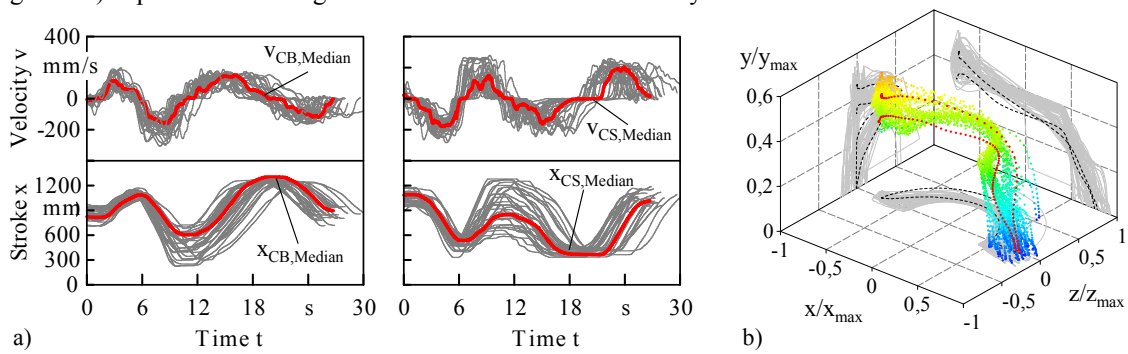


FIGURE 8. a) Normalized working cycles b) Normalized space curve

Equivalent reference cycles. Based on the investigation of the energetic behavior of measured cycles and methods found in literature, equivalent reference cycles should cover the energetically relevant operating points as well as their frequency and duration. To fulfill these requirements a combination of three dominant motion sequences is chosen. In figure 9 a) the energetic dependency of measured and simulated cycles is shown.

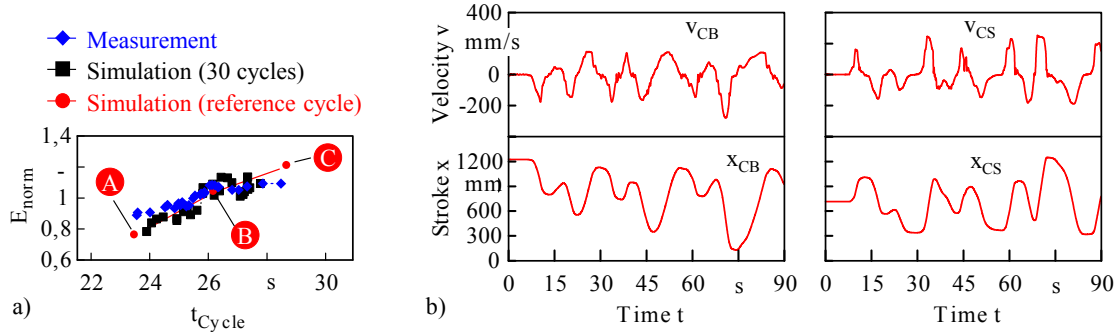


FIGURE 9. a) Comparison of normalized cycle energy b) Time plot of reference cycle

By combining the sections with shortest (A), longest (C) and mean cycle time (B) all important acceleration and duration characteristics may be covered, which is represented by the normalized cycle energy E_{norm}.

$$E_{norm} = \frac{\int P_{ICE,mech} dt}{\bar{E}_{mean}} \quad [t_i, t_{i+1}] \tag{10}$$

The resulting input data is plotted in figure 9 b). In order to be able to generate continuous trajectories, transition conditions must be formulated at the interface between the individual cycles. Adjustments of the fixed cycles, which become necessary when changing the machine size, geometry or power-setup are not applied. This may lead to deviations between target position and current position, especially when power requirements of the drive system are exceeded.

To analyze the energy flow behavior within a drive system, the energy distribution of the incorporated subsystems is suitable. Figure 10 displays the distribution of the hydraulic and mechanic energies for the main consumers over all conversion stages. In order to compare different simulation variants, the energy amounts are normalized to the sum of the hydraulic pumps' output energies (2a, 2b). Starting from this reference value (100%), the engine (1) has to provide about 175% mechanical energy at the motor's shaft. Besides pump losses (2a/2b, 3a/3b), the throttling losses at the main directional control valves (5, 7) are shown. The useful energy amount, provided by the cylinders (6, 8), is about 60 % of the normalized energy value. Considering the results in figure 10, it can be seen that regardless of chosen input data all energy shares show a similar distribution. There are minor deviations up to 10 %.

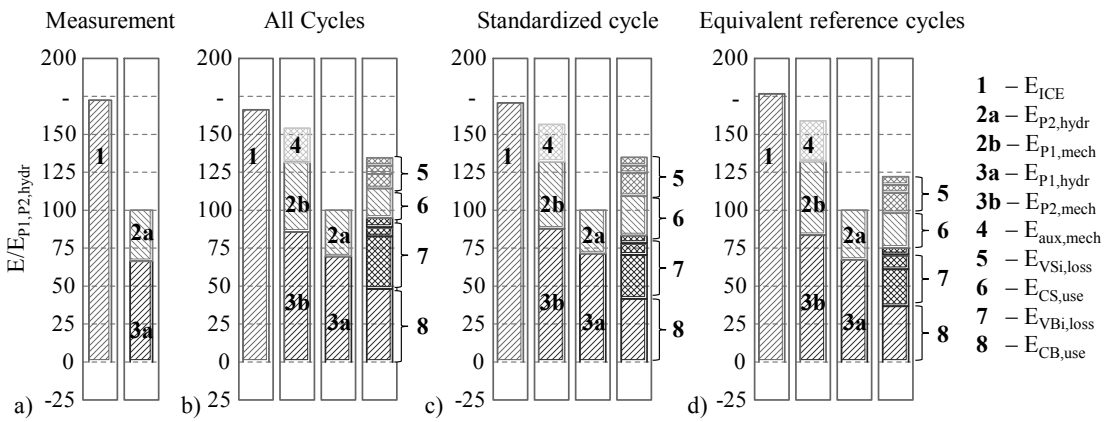


FIGURE 10. Energy distribution for different variants of cycle-input-data a) Measured Values, b) Simulation using complete cycle set, c) Standardized cycle, d) Equivalent reference cycle

Integral parameters, such as efficiency, total energy consumption or fuel consumption, are suitable for a compact characterization of complete machines or subsystems. However, one characteristic value cannot replace another one because a clear quantitative or qualitative allocation is not necessarily given. The delivered engine energy corresponds to the sum of the applied shaft energies of all connected loads. However, the fuel consumption varies depending on the location of the operating points in the characteristic engine map. Table 2 shows a comparison of simulated and measured fuel consumption data on the example of working task 1. All values are normalized to the measured average fuel consumption of working task 1 conducted with a load of 2.8 t.

TABLE 2. Fuel Consumption Evaluation

Cycle Description	Normalized, Average Fuel Consumption [%]	
	With Load	Without Load
Measurement	100	-
All cycles	99.4	83.4
Shortest cycle	84.6	68.8
Longest cycle	116.9	88.7
Standardized cycle	91.8	72.3
Equivalent reference cycles	100.7	79.4

The cycle selections' influence on fuel consumption is evident. There is a deviation of up to 30 % between the shortest and the longest single cycle. Using the standard cycle reduces the errors down to 8 %. The best results in terms of reproduction of the measured fuel consumption are realized using all cycles and the equivalent cycle. Another important influence may be investigated, when eliminating the load. Depending on the chosen input cycle the results vary over 30%. Here, it is obvious that energy and loss behavior of the drive system may be determined, but significant deviations for the prediction of fuel consumption are expected. The results obtained from methods as proposed in [11] and [22] reach their limits.

SUMMARY AND OUTLOOK

One of the biggest challenges in model-based efficiency analysis is the selection of appropriate motion and load profiles and thus realistic power requirements. Material handling excavators show an intermitting, repeating movement characteristic with varying environmental influences as well as highly complex operator-machine interaction. Since human diversity and the ability to permanently adapt is extremely hard to describe, empirical preset-trajectory definitions are still subject of investigations. In this regard, equivalent reference cycles should cover the energetic relevant operating points as well as their frequency and duration. The proposed method uses a combination of three dominant motion sequences. Results show a very good reproduction of the measured fuel consumption for the chosen work task. To cover the entire operating range of material handling excavators, typical application scenarios, which may be combined and weighted freely according to their fraction of total working hours, are used. Further, advancements relate to the adjustment of the fixed cycles which become necessary when the machine size, geometry or drive system setup changes. Suggestions like machine-size specific scaling factors or more complex control algorithms can be found in literature. Another approach, which is currently being investigated at TU Dresden, comprises the use of an online trajectory generator. The fundamental idea is to process offline geometric machine parameters to define the working space and a small number of supporting points for motion definition. In addition, an online adaption of the motion profile is carried out to be able to respond to power limitations or other boundary conditions.

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