AUTOMATED SYSTEM SYNTHESIS FOR ELECTRIFIED MOBILE MACHINERY

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ABSTRACT

The electrification of mobile machines leads to new drive solutions. Not only the electric drive components are newly deployed, but also the mechanical and hydraulic drive components can be utilized in a new or different way. This allows more efficient systems to be built and new advantages to be exploited. Conventional development processes require the developer to select a specific drive concept to be investigated at an early stage. The drive concept is then examined by means of simulations and/or experimental tests. The suitability of the drive system for the application is only evaluated after its detailed investigation and an iterative process. The overall process leads to a high effort and requires a large amount of time. Thus, it is economically not possible to evaluate many different system combinations with conventional methods. This paper proposes a tool to improve the development process. A methodology for an automated drive system evaluation is presented both structurally and in terms of how individual components are modelled. The methodology aims to deduce functioning system topologies based on load cycles. An analysis on the influence of different load cycles is therefore conducted.

Keywords: mobile machinery, system synthesis, electrification, excavator, algorithm

1. INTRODUCTION

In this paper the proposed methodology by Opgenoorth [1, 2] for algorithm-based automated evaluation of mobile machine drivetrain topologies, called TopoSelect is applied to the use case of an excavator. The presented methodology is suitable for the design of mobile electrical machines in general. This paper focuses specifically on excavators as an application example. Since excavators account for a large portion of mobile machinery in use [3–5] and their common drivetrain topologies are generally energy inefficient [3, 6–8], they are responsible for a large portion of CO_2 emissions in the mobile machinery sector [3, 9, 4]. Excavators are therefore an excellent example to show the challenges and opportunities in the electrification of mobile machinery.

2. STATE OF THE ART

2.1. Excavator topologies

A common drivetrain topology for excavators is shown in simplified form in **Figure 1**. It consists of three main parts, the energy source, the energy conversion and the energy output [10, 11]. Since electric powertrains have yet not been adapted on a large scale, the diesel internal combustion engine is still the dominant technology for the energy source for Non-Road Mobile Machinery (NRMM) and excavators in particular [12–14].

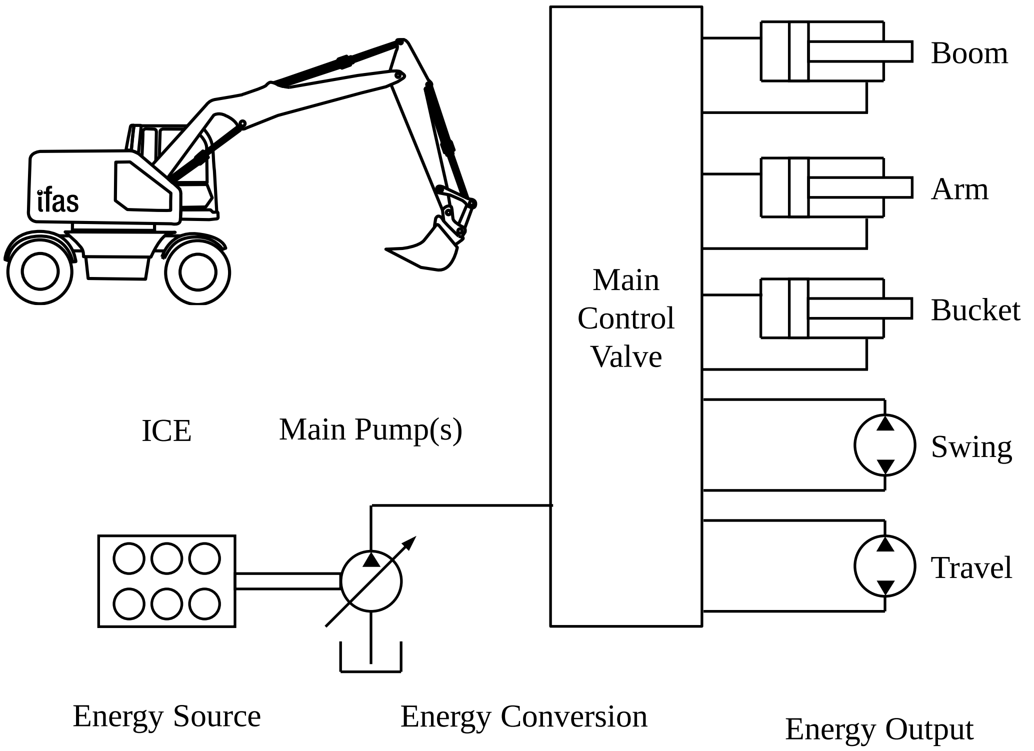

Figure 1: Simplified drivetrain topology of a traditional excavator [10]

The energy conversion consists of the hydraulic pump(s) and the Main Control Valve (MCV). The pump is powered by the engine and supplies hydraulic energy to the system. Traditionally, hydraulic systems of excavators rely on valve-controlled closed center or open center systems. Valve based systems allow the supply of multiple hydraulic drives using just a single pump. The main control valve in such a system, usually featuring multiple valve plates, divides and directs hydraulic flow based on operator joystick commands. It supplies energy to hydraulic drives (energy output), including the hydraulic cylinders of the boom, arm, and bucket, the swing drive for upper carriage rotation, and travel drives. These drives transform the hydraulic energy back into mechanical energy. This conversion powers the linear and rotational movement of the excavator components, enabling its various tasks like digging and grading. [3, 10, 11]

Common systems based on internal combustion engines have proven to be cost effective and reliable in the past [5, 15]. Despite this, electrifying mobile machines offers the advantage of using sustainable energy sources by integrating electrical storage or conversion systems like batteries or fuel cells, eliminating or reducing local emissions. The cost of the components required for this, specifically batteries and fuel cells, are one of the main challenges in the implementation of electric or hybrid drivetrains in mobile machines [2, 12].

As shown by Opgenoorth et al [10] for a 9 t-excavator, electrification can lead to efficiency gains by enabling decentralized direct electric drives and dynamic motor speeds. Machine design plays a crucial role in determining investment costs, particularly in terms of battery storage. In this context, efficiency gains through system design or better components become essential, as they can now lead to cost advantages. [1, 2, 10]

Figure 2 shows the energy flow through the drive train of an 18t wheeled excavator. It becomes apparent that significant losses occur in the whole drivetrain, mainly induced by the low efficiency of the internal combustion engine and systematic hydraulic losses. This means that only 6.4% of the input chemical energy of the diesel fuel are transformed into the mechanical energy used to perform the working task of the excavator. [3] Similar results have been found by Sturm for a comparable machine [8].

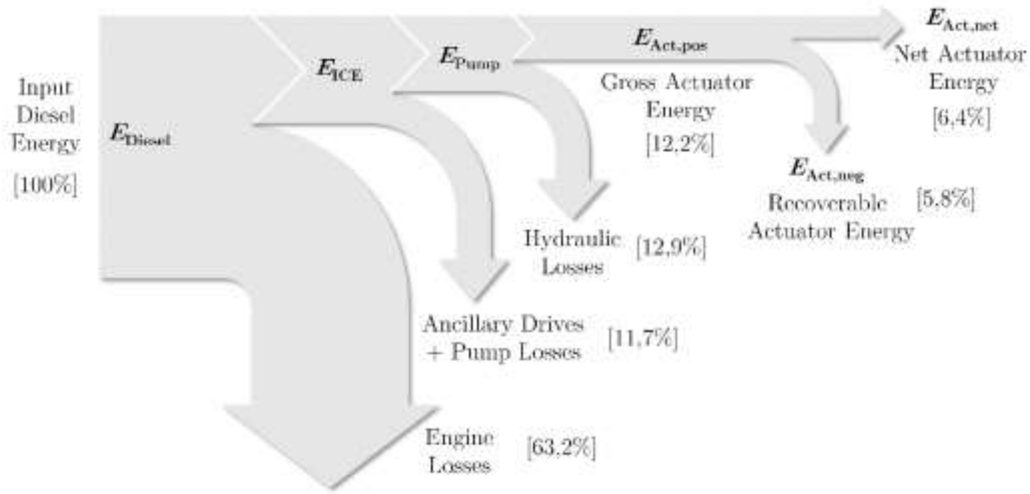

Figure 2: Sankey plot of a 18 t excavator performing a 90° dig and dump cycle [3]

Contemplating on this state of the art many possible topologies for integrating electric drives into mobile machines can be considered. To enable a holistic approach for designing electrified mobile machinery methods for systematic exploration of the possible design space are needed. The presented methodology, called TopoSelect, aims to assist engineers in this task by algorithm based automated evaluation of drivetrain topologies. [1, 2]

3. METHODOLOGY

3.1. System Topology Generation

The TopoSelect methodology separates the drivetrain of a mobile machine into eight subsystem layers. These consist either of mechanical subsystems (mechanical energy conversion), hydraulic subsystems (hydraulic or hydromechanical energy conversion) or electric subsystems (electric or electromechanical energy conversion). **Figure 3** shows the eight layers that are considered in the generation of a drive train topology. The system is calculated backwards from drives to energy source, i.e., the first layer starts with the force and speed, or torque and speed load cycle of the considered mechanical drives. [1, 2]

Between subsystems, the important internal variables are transferred. For the mechanical connections this is speed and torque, for the hydraulic pressure and volume flow and for the electrical current and voltage. Power and efficiencies can then be calculated from these internal variables. [1, 2]

TopoSelect is meant for the development of electric mobile machines, so in all variations the main power supply is always electric. In this application only batteries are considered as the electric power source. Fuel cells or other electrical power sources are not included. This means, the last three subsystems for every topology variation in this application are always electric motor, inverter, and battery, as shown in Figure 3. [1, 2]

A certain path, i.e., a certain drive topology, does not have to include all eight subsystems. This means, that the hydraulic subsystems are generally optional, despite being often used in mobile applications. This enables the option of direct electric drives (optionally paired with a mechanical transmission). For example, for the excavator application, drive trains can be considered in which the linear actuators are hydraulic, but the upper carriage is rotated by an electric swing drive. This is the case with some tracked excavators such as the Kobelco HB365LC/NLC-3 [16] or the Komatsu

HB215LC-3 [17]. The use of electric track drives can also be evaluated with the presented methodology. If a certain path includes a hydraulic system, the linear or rotational mechanical movement is converted into hydraulic variables in the subsystem of the hydraulic converter. These are transferred to the hydraulic system. Constant pressure, open center and load sensing systems as well as displacement control are implemented. [1, 2]

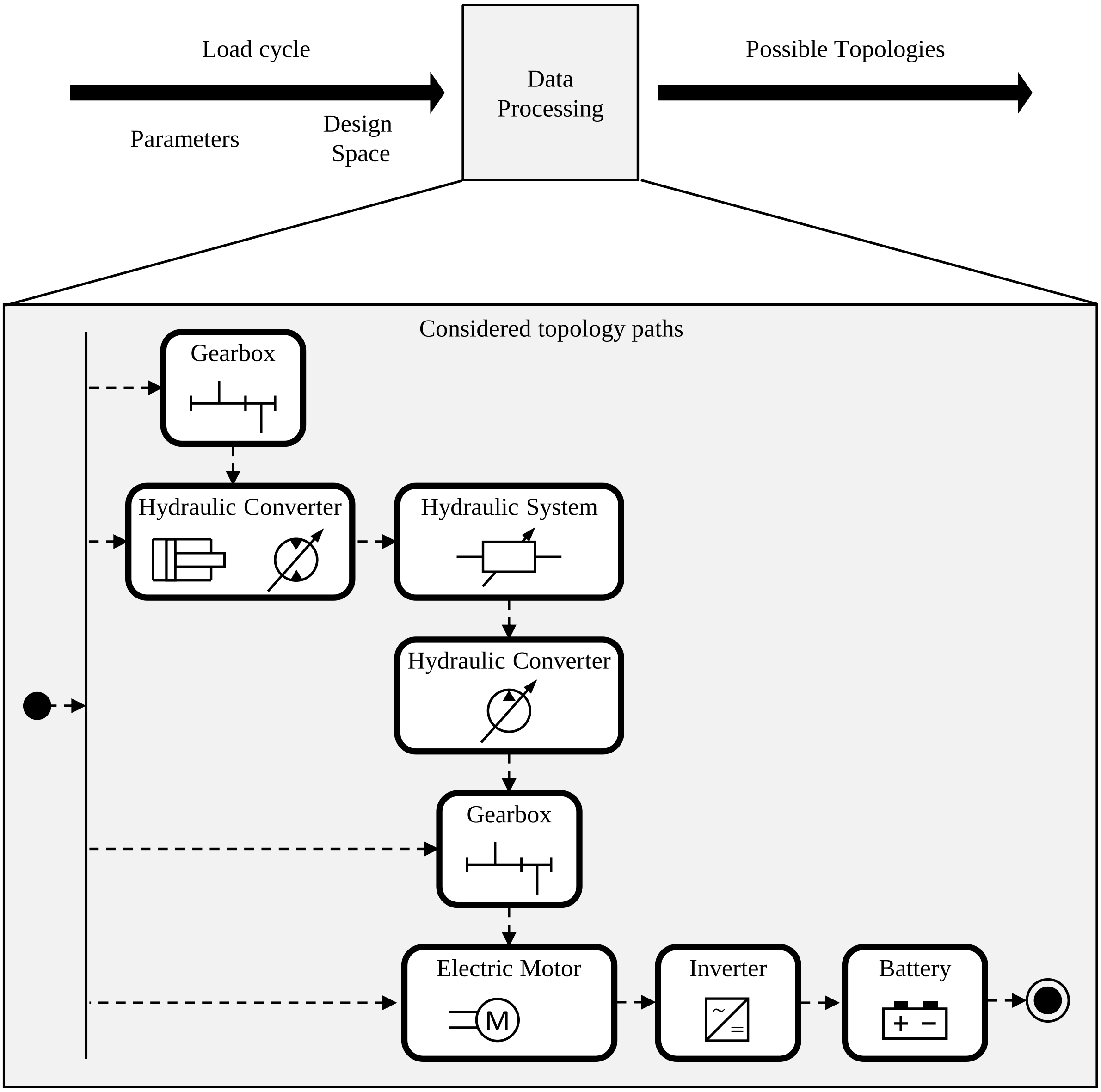

Figure 3: Topology generation based on subsystems

For each subsystem shown in Figure 3 various components of different type and nominal power with different parameters are implemented in an underlying data base. Based on the number of selected components per layer, the number of possible variations can be deduced with equation (1)

$$n_{comb} = \prod_{i}^{8} n_{sub,i} \tag{1}$$

For example, five components selected for every layer result in the calculation of $5^8 = 390625$ variations. Because of this large number of possible paths, the performed calculations within the subsystems must be efficiently implemented regarding computation time, to achieve acceptable performance of the optimization. This is why the calculations within TopoSelect are based on static analysis of operating points in which design parameters like cylinder diameters or pump displacement volumes are determined, resulting in fast to calculate operations without algebraic loops. This means the methodology focusses onto the energy balance rather than the dynamic properties of the evaluated systems.

For the size of the hydraulic cylinders, for example, a minimum required rod diameter is calculated from the maximum acting force in relation to the buckling safety. The system pressure and the acting forces from the load cycle determine the minimum required piston area. These two variables are used to determine the minimal cylinder size from a range of standardized cylinder sizes.

3.2. Software implementation

The presented methodology is realized through a MATLAB based Software tool. The overall architecture is shown in simplified form in **Figure 4**.

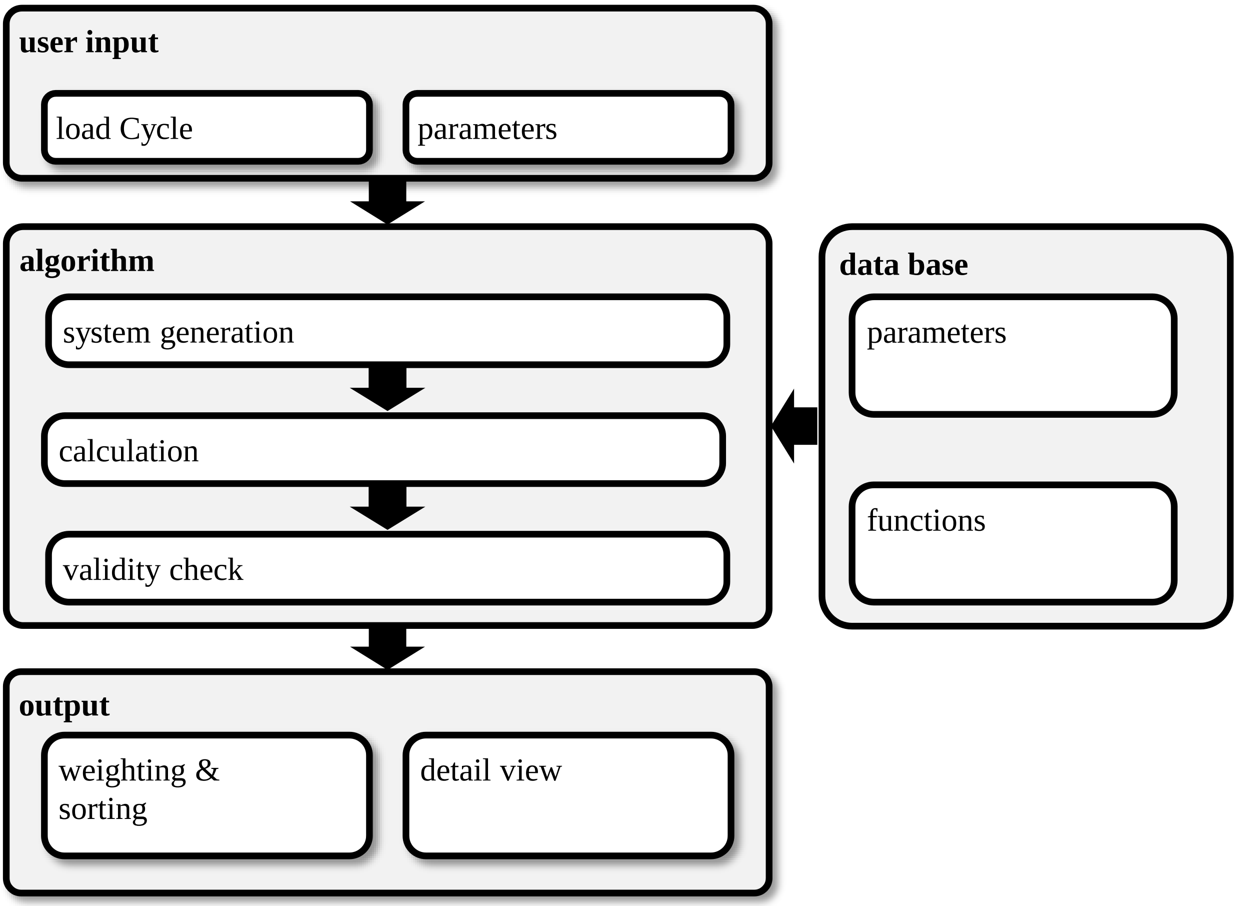

Figure 4: TopoSelect software architecture [2]

The software tool can be broken down into four mayor sections. The user input, the algorithm, the data base, and the output.

User Input

In this interface the user specifies the system requirements with the input of a specific load cycle. Which set of subsystems should be considered in the design space can also be chosen to limit the number of possible variations. The user can also define a set of constraints such as the emission equivalents and cost of electricity, the inverter DC-link voltage, and details regarding the planned workload of the machine.

Algorithm

The software tool generates all possible combinations according to the method explained in chapter 3.1 and calculates the internal variables. Invalid combinations are eliminated. The calculation process places special demands on the software. One of the biggest challenges is the interaction with the database of functions and properties. In particular, the calculation of individual components is associated with significant difficulties. This is because the calculations must be performed quickly, considering the numerous possible combinations, and complicated calculation tasks. To solve this problem, the use of software that can perform parallel calculations with multidimensional data structures is essential. Since most system computations follow a unidirectional flow, a direct implementation is feasible. The unidirectional structure is established by predefined interfaces. However, certain constraints are indispensable in the detailed analysis. For example, the calculation of the inverter losses depends on the battery voltage, which is not known at the time of calculation. In such cases, initial assumptions are required.

Data Base

The performed computations require a data base of components, filled with parameters regarding size, cost, efficiency, and emitted emissions during production. Information about the compatibility with other subsystems is also included. Various drive systems are created in the methodology. These include, for example, gearboxes, hydraulic components, electric machines, power converters, energy storage systems and various types of hydraulic systems. The selection of stored components is illustrated here using the example of hydraulic systems. The hydraulic systems implemented are the constant pressure system, the load sensing system, the open center system with one and two circuits and the displacement control system. The system calculation includes the determination of the pressure losses depending on the required volume flows and also, in the case of the multi-circuit open-center systems, the determination of the complex valve logic. In other categories, however, specific components are stored. In the case of the e-machine, for example, machines with rated outputs of 20 to 400 kW are available. Three variants with different nominal and maximum speeds are included for each of these power classes. A data set with lookup tables for the electrical operating points and the losses as a function of the mechanical operating points is stored for each variant consisting of nominal power and nominal speed.

Output

The output section includes an interface, where the user can make choices regarding the importance of certain properties of the system through associating weights to parameters which are used to rank all the calculated system topology variations. For example, the user can specify if the efficiency or the cost of a specific application is more important. As a result, the software supplies a ranked list of systems to the user based on the made choices. Details, which components form a specific topology, its parameters, and plots of the internal variables, are displayed through a graphical user interface.

4. WEIGHTING METHOD

The following chapter describes in detail how the ranked list of systems as the output is determined. In TopoSelect the Method of Weighted Sums is used. This method is simple and precise, but requires the calculation of a performance value [18]. The following list of criteria can be used to evaluate the performance of the systems:

- Efficiency [%]
- Hourly energy cost [€/h]
- Total cost of ownership [€]

- Investment cost [€]
- Operating cost [€/h]
- Total $C0_2$-emmisions [g]
- Initial $C0_2$-emmisions [g]
- Operating $C0_2$-emmisions [g/h]

Within the algorithm calculation (compare Figure 4) the investment cost and initial C02-emmisions of a specific combination are obtained from the component database using the calculated component sizes. The system efficiency can be calculated from the internal variables (compare section 3.1) of each subsystem layer, the hourly energy cost and operating C02-emmisions are determined with the calculated required power and the user specified cost of energy and C02-emmisions of the used power mix. The operating cost and operating C02-emmisions describe the produced cost and emissions from machine maintenance and can also be calculated for a specific combination of subsystems/components using the underlying component database and the intended daily and annual usage and designed lifetime defined by the user. The total cost of ownership and total C02-emmisions can be calculated from the other criteria. This means that for every valid system topology a value describing its performance regarding the mentioned criteria is obtained.

Through another GUI the user can define the importance of each individual criterion j within the scope of the desired application by inputting a value from 0 to 10 for the criterion weights w_j. By normalising the adjusted weights w_j^{adj} are then calculated (2).

$$w_j^{adj} = w_j \cdot \left(\sum_{j=1}^{n_{crit}=8} w_j \right)^{-1} \tag{2}$$

The Score WS_i of a Combination i is determined according to equation (3) from the adjusted criterion w_j^{adj} and the performance value a_{ij} in terms of the criterion j [18].

$$WS_i = \sum_{j=1}^{n_{crit=8}} w_j^{adj} \cdot a_{ij} \quad \text{with } a_{ij} \in [0,1] \tag{3}$$

With this calculation a value ranging from 0 to 1 is obtained for WS_i,which is used to rank all valid combinations. The required performance value a_{ij} of a combination i with respect to criterion j is calculated by one of two linear cost functions, depending on whether the value of a particular criterion is to be maximized (efficiency) or minimized (costs, emissions). These cost functions can be expressed with equation (4) and represent an interpolation between (0,1) or (1,0) and the maximal and minimal value of the criterion j for all valid topologies.

$$a_{ij} = \begin{cases} \dfrac{c_{ij} - \min(\boldsymbol{c_j})}{\max(\boldsymbol{c_j}) - \min(\boldsymbol{c_j})}, for\ efficiency \\ 1 - \dfrac{c_{ij} - \min(\boldsymbol{c_j})}{\max(\boldsymbol{c_j}) - \min(\boldsymbol{c_j})}, else \end{cases} \tag{4}$$

In this notation $\boldsymbol{c_j} = \{c_{1j,} c_{2j,}, c_{1j,} \dots c_{nj,}\}$ is the set of values of all n valid combinations regarding the criterion j and c_{ij} the specific value for the topology i. For example, considering the investment costs criterion, this calculation results in a performance value of 1 for the topology with the lowest investment costs and a performance value of 0 for the topology with the highest investment costs. All other performance values are relative to these and therefore lie between 0 and 1.

By sorting the list of topologies according to their calculated score a sorted and ranked list of drivetrain topologies suited to the used load cycle and operating conditions specified is obtained.

5. APPLICATION: EXCAVATOR

To showcase the capability of the proposed method, the data of a dig and dump cycle of an 18 t wheeled excavator is used as input data. It contains the load forces and velocities of the three hydraulic cylinders powering the motion of the boom, arm and bucket and the torque and the rotation speed of the upper carriage. These load cycles are shown in state space representation in Figure 5

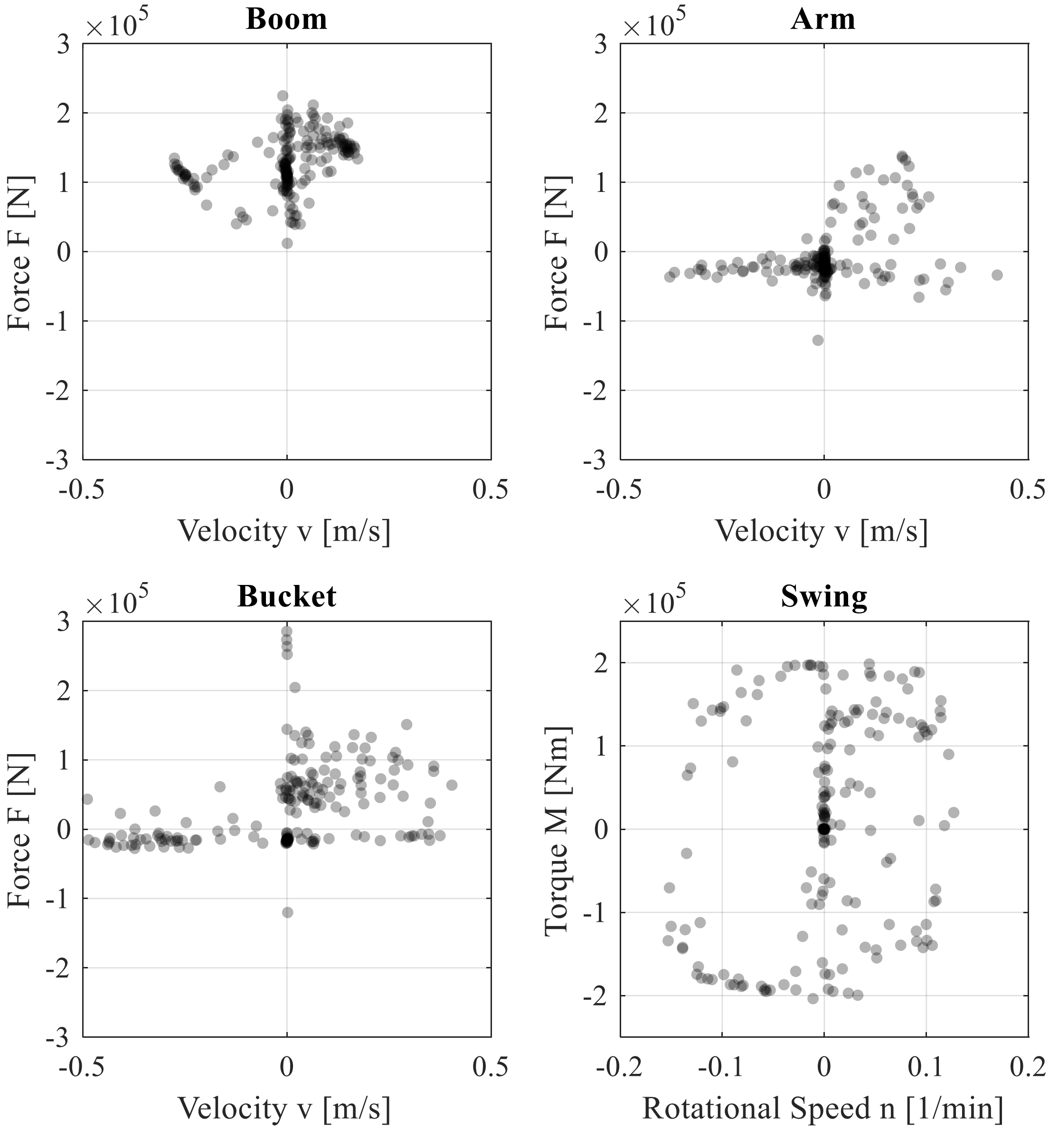

Figure 5: Load Cycle Dig and Dump

Figure 6 shows the Graphical User Interface (GUI) of the data input interface of the TopoSelect tool. The shown load cycle has been selected, displayed as force, velocity, torque, and rotation speed over time in the right half of the window. The left half of the GUI enables the configuration of parameters and definition of the design space. As values for the C02-emission parameter describing the used power mix 375 g/kWh was chosen. In addition to that, an electricity cost of 0.3 €/kWh, a daily usage of 5 hours, a designed lifetime of 10,000 hours, an annual usage of 150 days was set. The DC-voltage between the inverter and battery is specified with 750 V. The “toggle components”-button in the lower left section of the window opens another GUI in which the limitations of the design space can be specified by including or excluding specific subsystems/components from the calculation. For this application five different output mechanical transmissions and the direct electrical and hydraulic drives were considered, also two options for the hydraulic converters, three different hydraulic systems (open center, load-sensing and constant-pressure), six different hydraulic pumps, six different input mechanical transmissions, eight different electric machines, seven different inverters and three different batteries were selected.

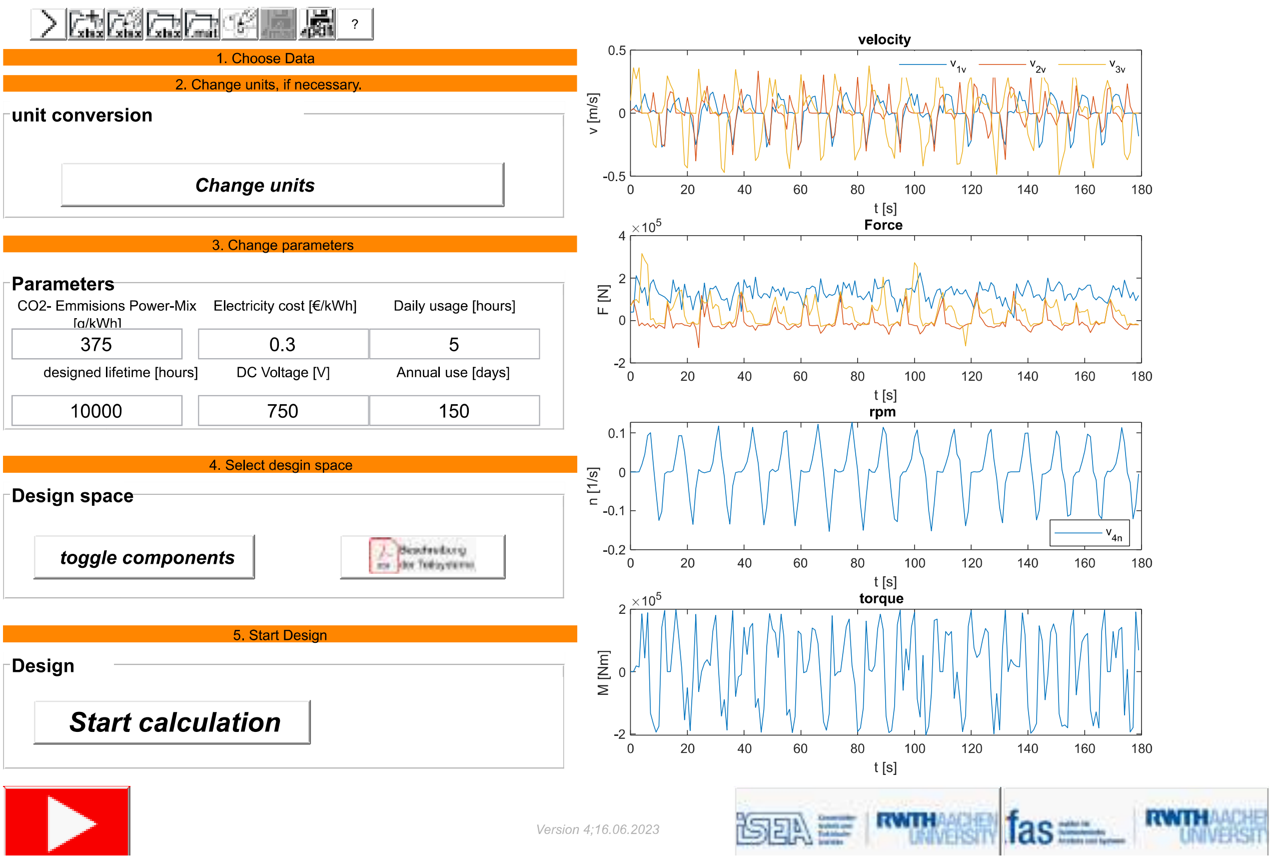

Figure 6: Graphical User Interface

According to (1) this means 254016 possible combinations. From this TopoSelect determined and calculated 405 valid combinations with the algorithm presented in chapter 3. In this example application two of eight possible parameters were used to evaluate the combinations, efficiency (2/10) and total cost of ownership (6/10).

The list is sorted according to the specified parameters. The chosen parameters in this application, efficiency and total cost of ownership are displayed for all valid combinations in a bar plot shown in **Figure 7**. In this representation combination 1 has the best and combination 405 the lowest score. The best combination has the highest efficiency paired with the lowest total cost of ownership. The suggested topology of this system consists of a mechanical transmission paired with a secondary controlled hydraulic motor as a swing drive and hydraulic cylinders to drive the boom, arm, and bucket. These are connected to the hydraulic pump through an Open-Center hydraulic system. A hydraulic pump with a constant displacement volume is selected. The variation of the supplied hydraulic flow is achieved by a variable drive speed. The pump is connected via an electric motor to the inverter and battery.

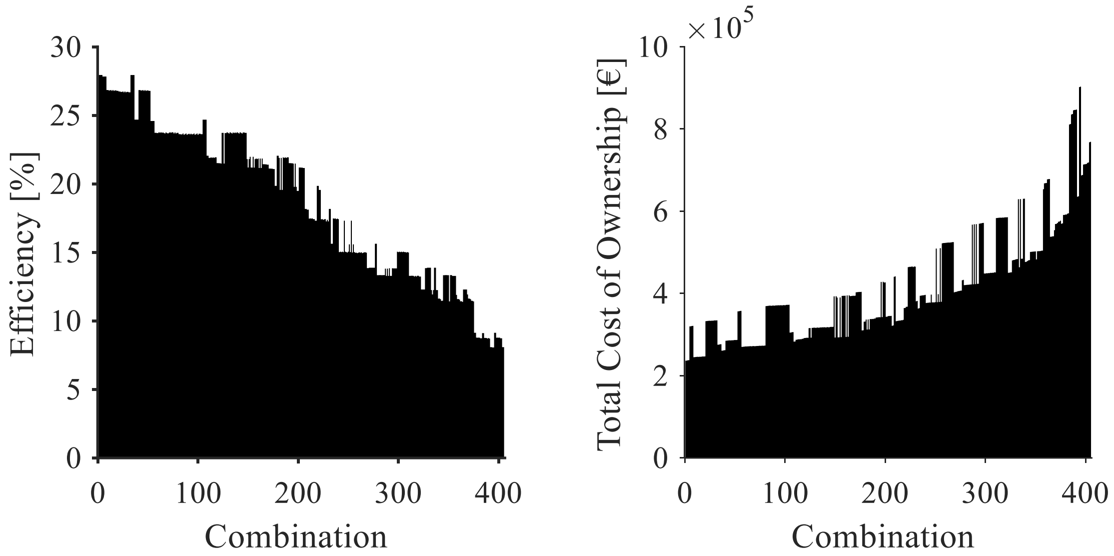

Figure 7:Sorted combinations

5.1. Interpretation

The results obtained must be interpreted considering the underlying database. The more accurate the parameters describing the components, the more accurate the calculated results will be. Since some of the relevant parameters, e.g., the exact costs, detailed efficiency maps, or emissions generated in the production of a particular component, are not easily specified or available in this context, most of the underlying database in this application example does not have the desired accuracy. A more accurate data base would therefore facilitate the applicability of the calculated results. This means that the presented results should only be interpreted as a proof of concept of the capability of the used method rather than a universally applicable recommendation for the drivetrain design of electrified excavators. In addition to that, it must be noted that excavators are often used for a wide range of tasks [4]. That is especially true for smaller machines. This means a proper design approach should include the use of multiple load cycles.

6. SCOPE AND INTENDED USE

The added value contributed by the presented methodology is the systematic and extensive implementation of standard dimensioning calculations, combined with a weighting and sorting algorithm. This enables the systematic investigation of all possible solution combinations based on a component database, certain boundary conditions and a load cycle. In contrast to classical methods, this makes it possible to consider a massive number of variants at an early stage in the design process of an electrically driven mobile machine, where the requirements but no functional structure have yet been defined. The methodology is not intended to optimize a fixed topology of a drive train, but to identify a group of promising topologies. This is particularly important in the development of electrically powered mobile machinery, as completely new drive topologies are now feasible. The method presented is therefore intended to contribute to a holistic view of the entire solution space. Once a selection of topologies has been identified, the design process must be continued with detailed design and other methods, e.g. dynamic simulations.

7. CONCLUSION AND OUTLOOK

As stated above the successful application depends heavily on the availability of detailed and precise component data. However, such databases are not publicly accessible or are unsuitable for such a connection with the current state of development. Therefore, the major task in applying the methodology to a real machine design process is to gather and implement an accurate component data base. In principle, when connected to a comprehensive database system of component manufacturers, the presented methodology is a good approach for the holistic discussion of possible powertrain topologies of electrified mobile machines.

To further complement the design process future work could focus on the implementation of the automated evaluation of multiple load cycles or load collectives. Efforts to improve computation time might enable the inclusion of more sophisticated calculations within the subsystems itself. Both approaches would facilitate the practicability of the presented design methodology.

8. ACKNOWLEDGEMENTS

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NOMENCLATURE

a_{ij}	Performance value	[-]
$\boldsymbol{c_j}$	Set of criterion values	[-]
c_{ij}	Criterion value	[varying]
n_{comb}	Number of possible combinations	[-]
n_{crit}	Number of criteria	[-]
$n_{sub,i}$	Number of selected components in layer i	[-]
w_j	Criterion weight	[-]
w_j^{adj}	Adjusted criterion weight	[-]
WS_i	Combination Score	[-]
DC	Direct current	
GUI	Graphical User Interface	
NRMM	Non Road Mobile Machinery	
MCV	Main Control Valve	

REFERENCES

[1] Opgenoorth A, Loewenherz R, Doncker RW de et al. (2023) Untersuchung einer automatisierten Systemsynthese elektrifizierter mobiler Arbeitsmaschinen. In: Geimer M (ed) Hybride und energieeffiziente Antriebe für mobile Arbeitsmaschinen Karlsruhe: 9. Fachtagung, 28. Februar 2023. KIT Scientific Publishing, Karlsruhe, pp 49–71

[2] Opgenoorth A (2023) ALGORITHM BASED SYSTEM SYNTHESIS OF ELECTRIFIED MOBILE MACHINES. In: Tatiana Minav (ed) The 18th Scandinavian International Conference on Fluid Power, SICFP'23, Tampere, Finland

[3] Vukovic M, Leifeld R, Murrenhoff H (2017) Reducing Fuel Consumption in Hydraulic Excavators—A Comprehensive Analysis. Energies 10:687. https://doi.org/10.3390/EN10050687

[4] Fecke M (2018) Bewertung der Energieeffizienz von Baumaschinen mithilfe einer praxisnahen Lastzyklusentwicklung für einen In-Situ-Test. Bergische Universität Wuppertal

[5] Leifeld R (2022) Hybridmodul für elektrohydraulische Antriebssysteme von Baggern. Shaker Verlag, Düren

[6] Casoli P, Scolari F, Minav T et al. (2020) Comparative Energy Analysis of a Load Sensing System and a Zonal Hydraulics for a 9-Tonne Excavator. Actuators 9:39. https://doi.org/10.3390/act9020039

[7] Salomaa V, Minav T, Mattila J et al. (2018) Efficiency Study of an Electro-Hydraulic Excavator. In: Murrenhoff H (ed) 11th International Fluid Power Conference: Fluid Power Networks. RWTH Aachen University, Aachen, pp 372–385

[8] Sturm C (2015) Bewertung der Energieeffizienz von Antriebssystemen mobiler Arbeitsmaschinen am Beispiel Bagger. KIT Scientific Publishing, Karlsruhe

[9] Fecke M, Helmus M (2015) Standardisierung definierter Lastzyklen und Messmethoden zur Energieverbrauchsermittlung von Baumaschinen. In: Forschungsvereinigung Bau- und Baustoffmaschinen e.V. (ed) Proceedings of the 6th Fachtgaung Baumaschinentechnik: Maschinen, Prozesse, Vernetzung, pp 113–122

[10] Opgenoorth A, Quabeck S, De Donker RW et al. (2020) Challenges and possibilities of the integration of electric drives in mobile machinery. In: Technische Universität Dresden (ed) 12th International Fluid Power Conference, vol 1. Dresdner Verein zur Förderung der Fluidtechnik e. V. Dresden, Dreseden, pp 471–480

[11] Murrenhoff H, Eckstein L (2014) Fluidtechnik für mobile Anwendungen: Umdruck zur Vorlesung, 6., überarb. Fassung. Reihe Fluidtechnik, vol 5. Shaker, Aachen

[12] Lajunen A, Sainio P, Laurila L et al. (2018) Overview of Powertrain Electrification and Future Scenarios for Non-Road Mobile Machinery. Energies 11:1184. https://doi.org/10.3390/EN11051184

[13] Lindgren M, Hansson P-A (2004) Effects of Transient Conditions on Exhaust Emissions from two Non-road Diesel Engines. Biosystems Engineering 87:57–66. https://doi.org/10.1016/j.biosystemseng.2003.10.001

[14] Radermacher T, Merx M, Sitte A et al. (2021) Potentialstudie Energie-/ Kosteneinsparung in der Fluidtechnik: Abschlussbericht. Climate Change

[15] Vukovic M (2017) Hydraulic hybrid systems for excavators. Dissertation, Rheinisch-Westfälische Technische Hochschule Aachen; Shaker Verlag

[16] Kobelco (2021) Fully equipped Hybrid SK210HLC-10 with 2 piece boom in the Netherlands. https://www.kobelco-europe.com/news/fully-equipped-hybrid-sk210hlc-10-with-2-piece-boom-in-the-netherlands/

[17] Komatsu (2016) Komatsu Europe International N.V. Presents New HB365LC-3 Hybrid Excavator. https://www.komatsu.eu/Assets/GetPressReleaseByProductName.aspx?id=HB365LC/NLC-3%20Hybrid&langID=de

[18] Bender B, Gericke K (2021) Pahl/Beitz Konstruktionslehre. Springer Berlin Heidelberg, Berlin, Heidelberg