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Energy management control strategies for hybrid construction equipment

Load sharing between diesel and electric prime movers in parallel hybrid excavators

A thesis for the degree of Master of Science in Mobility Engineering

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Cover: An excavator manufactured by Volvo Construction Equipment

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Abstract

This study involves the development and evaluation of energy management strategies for hybrid excavators. A simulation-based framework was established in MATLAB and Simulink to model a parallel-hybrid powertrain with a diesel engine and electric motors driving the central hydraulic pump of an excavator. The load power from the pump was split between the prime movers by controllers programmed to follow certain strategies. Dynamic Programming (DP), Equivalent Consumption Minimisation Strategy (ECMS), and a rule-based approach were formulated and assessed under varying operating conditions. The evaluation was conducted on a 50-tonne excavator using drive cycles with high, medium, and low power demands, subject to the operational constraints of using a smaller engine, maintaining the battery state of charge (SoC) balance over each drive cycle, and maintaining constant hydraulic pump speed under load.

Results indicate that a carefully designed rules-based strategy can achieve performance comparable to ECMS and the globally optimal solution indicated by the DP, while requiring substantially lower computational requirements than the other two, thereby enhancing its suitability for real-time implementation. Fuel consumption reductions were observed across all cycles, with more pronounced improvements in medium- and low-power scenarios. Combined fuel savings across all drive cycles for the 50-tonne machine were measured at 6-8%. These learnings were further applied to a high-power cycle of a 75-tonne excavator, with similar results. The study thus demonstrates that a hybrid configuration comprising a smaller internal combustion engine, supplemented by electric machines, can deliver operational capability equivalent to that of a larger combustion engine. This enables increased flexibility in powertrain design, allowing manufacturers to expand machine capacity with their existing engines.

An assessment of the total cost of ownership (TCO) was also conducted for the 50-tonne hybrid, incorporating both fuel savings and machine cost increases compared to the conventional machine. For this, an estimate of the required battery size was also made. Overall, the results demonstrate that hybridisation, combined with effective energy management strategies, can significantly enhance the efficiency, adaptability, and economic feasibility of construction machinery.

Keywords: hybridisation, energy management control, parallel hybrid, Total Cost of Operation, fuel savings, excavators.

Reglerstrategier för energihantering inom hybrida anläggningsutrustningar
Kraftfördelning mellan diesel- och elmotorer inom parallell-hybrida grävmaskiner
UPASANA NANDAGIRI
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Sammanfattning

Denna studie omfattar utveckling och utvärdering av reglerstrategier för energihantering inom hybridgrävmaskiner. Ett simuleringsbaserat ramverk utvecklades i MATLAB och Simulink för att modellera en parallellhybrid drivlina där en dieselmotor och elmotorer driver grävmaskinens hydraulpump. Pumpens lasteffekt fördelades mellan kraftkällorna genom regulatorer programmerade att följa olika strategier. Dynamic Programming (DP), Equivalent Consumption Minimisation Strategy (ECMS) samt en regelbaserad strategi formulerades och utvärderades under varierande driftförhållanden. Utvärderingen genomfördes på en 50-tons grävmaskin med körcykler som representerade höga, medelhöga och låga effektbehov, under begränsningarna att använda en mindre dieselmotor, upprätthålla batteriets laddningsnivå (SoC) över varje körcykel samt bibehålla konstant varvtal på hydraulpumpen under belastning.

Resultaten visar att en väl utformad regelbaserad strategi kan uppnå prestanda jämförbara med ECMS och den globalt optimala lösning som erhålls med DP, samtidigt som den kräver betydligt lägre beräkningskapacitet än de två andra metoderna. Detta gör strategin mer lämpad för realtidsimplementering. Minskad bränsleförbrukning observerades i samtliga körcykler, med tydligare förbättringar vid medelhöga och låga effektbehov. Den sammanlagda bränslebesparingen för 50-tonsgrävmaskinen uppmättes till 6–8 % över alla körcykler. Dessa lärdomar tillämpades även på en högeffektcykel för en 75-tons grävmaskin, med liknande resultat. Studien visar därmed att en hybridkonfiguration bestående av en mindre förbränningsmotor, kompletterad med elektriska maskiner, kan leverera motsvarande operativ kapacitet som en större förbränningsmotor. Detta möjliggör ökad flexibilitet i drivlinedesignen och ger tillverkare möjlighet att öka maskinkapaciteten med befintliga dieselmotorplattformar.

En analys av den totala ägandekostnaden (TCO) genomfördes också för 50-tonshybriden, där både minskade bränslekostnader och ökade maskinkostnader jämfört med den konventionella maskinen inkluderades. I samband med detta gjordes även en uppskattning av den erforderliga batteristorleken. Sammantaget visar resultaten att hybridisering, i kombination med effektiva energihanteringsstrategier, kan förbättra anläggningsmaskiners effektivitet, anpassningsförmåga och ekonomiska genomförbarhet avsevärt.

Nyckelord: hybridisering, parallell-hybrid, energihantering, reglersystem, total ägandekostnad, bränslesparande, grävmaskiner.

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Upasana Nandagiri
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Gothenburg, May 2026

List of Acronyms

Below is the list of acronyms that have been used throughout this thesis listed in alphabetical order:

BEV	Battery Electric Vehicle
BSFC	Brake Specific Fuel Consumption
DP	Dynamic Programming
ECMS	Equivalent Consumption Minimisation Strategy
GSP	Global Simulation Platform
PMP	Pontryagin's Minimum Principle
RMSE	Root Mean Square Error
RPM	Revolutions Per Minute
SoC	State of Charge
TCO	Total Cost of Operation

Nomenclature

Below is the nomenclature of indices, sets, parameters, and variables that have been used throughout this thesis.

I_{bat}	Battery current	A
I_{em}	Motor current	A
J	Moment of inertia	$kg\ m^2$
J_{em}	Moment of inertia of electric motor	$kg\ m^2$
J_{ice}	Moment of inertia of internal combustion engine	$kg\ m^2$
K_i	Integral gain	W
K_s	Proportional gain	W
k_p	Power allocation factor	W
$\dot{m}_{batt}$	Equivalent fuel consumption of battery power	$kg\ s^{-1}$
$\dot{m}_{fuel}$	Mass flow rate of fuel	$kg\ s^{-1}$
n_{series}	Number of cells in series	$-$
$n_{parallel}$	Number of cells in parallel	$-$
P_{bat}	Battery power	W
P_{em}	Motor output power	W
P_{fuel}	Fuel power	W
P_{ice}	Engine output power	W
P_{load}	Load power	W
P_{pm}	Prime mover power	W
Q_{bat}	Battery capacity	Ah
Q_{LHV}	Lower heating value of fuel	$J\ kg^{-1}$
R_{int}	Internal resistance of the battery	Ω
S	Equivalence factor	Ω
T_{em}	Electric motor torque	$N\ m$
T_{ice}	Combustion engine torque	$N\ m$
T_{load}	Load torque	$N\ m$

T_{pm}	Prime mover torque	$N\ m$
V_{bat}	Battery terminal voltage	V
V_{oc}	Open circuit voltage	V
β	Cost function for minimisation	$-$
ω_{em}	Rotational speed of electric motor	$rad\ s^{-1}$
ω_{ice}	Rotational speed of internal combustion engine	$rad\ s^{-1}$
ω_{load}	Rotational speed of load pump	$rad\ s^{-1}$
ω_{pm}	Rotational speed of prime mover	$rad\ s^{-1}$
ω_{pump}	Rotational speed of hydraulic pump	$rad\ s^{-1}$
η_{em}	Electric motor efficiency	$-$
η_{ice}	Engine efficiency	$-$

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1

Introduction

This chapter discusses the thrust behind this study from corporate and environmental perspectives. The structure of the report is also explained.

1.1 Why we need hybrid construction equipment

1.1.1 Environmental perspective

The construction industry is a significant greenhouse gas emitter and fossil fuel consumer. Buildings as a whole - including their construction, useful life, and demolition - were estimated to emit around 33% of all anthropogenic carbon dioxide in 2002 by the IPCC.[1] The bulk of these emissions come from the manufacturing and preparing of the building materials themselves; on-site construction and demolition phases of that life cycle, where machines such as excavators, bulldozers, and dump trucks are used, are estimated to contribute to between 5-11% of the emissions, varying depending on location, material, and size of the project.[2][3]

However, even this number is quite large in absolute terms - the Danish thermal engineering and electronics firm Danfoss Power Solutions stated, citing a 2022 IDTechX report in a white paper at the 2023 UIA World Congress of Architects in Copenhagen, that construction equipment and vehicles emit approximately 400 megatonnes of carbon dioxide annually, which was almost half as much as the combined emissions of the entire aviation industry. About half of these emissions were estimated to come from excavators, with large excavators with a capacity greater than 10 tonnes alone contributing to 92% of all excavator CO_2 emissions.[4][5]

In addition, diesel-powered construction equipment emit significant amount of pollutants such as oxides of sulphur and nitrogen, as well as unburnt hydrocarbons. In the EU, these are regulated by Regulation 2016/1628 of the EU Parliament and Council.[6] As countries around the world aim to reduce their carbon emissions and improve their urban air quality, such requirements will become stricter. This means that excavators in the future must burn less fuel.

1.1.2 Corporate perspective

Burning less fuel (or no fuel) is also of interest to manufacturers of construction equipment because of the possibility to offer a reduced Total Cost of Operation

(TCO) to customers. Apart from full electrification, this can be achieved either by running existing combustion engines more efficiently, or by using smaller engines with assistance from other sources, i.e., by hybridisation.

The ability to use smaller engines to provide the same performance in a machine also opens up avenues for manufacturers to use their existing engine range to offer larger machines, without having to design or purchase new engines. This effect is particularly pronounced with very heavy machines, where the jump from, say, 12-litre engines to 20-litre engines may be prohibitively expensive, making larger machines unprofitable to manufacture.

1.1.3 Challenges with full electrification, and hybrids as an answer

The most common type of non-fossil-fuel-driven vehicle is a battery electric vehicle (BEV) with a lithium-ion battery. Such machines are seeing wider use every day, with improvements in battery chemistries and charging infrastructure making their low running cost more attractive. However, some challenges remain. The poor energy density of lithium-ion batteries compared to diesel fuel has a particularly strong effect on construction vehicles, which must operate for as long as possible within the working day, under heavy duty cycles to maximise site productivity.[7] This low energy density also requires batteries to be very large and heavy, which apart from increasing energy use, also makes machine costs very high, which can push breakeven times versus combustion machines into the range of several years.

The Li-ion battery technologies with the best energy densities also have an excess of rare-earth minerals such as cobalt, which are expensive and also linked to human rights abuses in the mining process. Battery technologies with more plentiful materials, such as lithium-iron-phosphate, have lower energy density.

A promising alternative, therefore, is a hybrid machine which uses electric motors fed by batteries in the regions where the diesel engine is fuel-inefficient and highly polluting, such as ramp-up and high load conditions. Alternatively, as discussed in the previous section, the engine size can itself be reduced, while the motors can be used to add to the engine torque to meet the original performance requirements. In both these approaches, the battery-motor system can be smaller than in a full BEV, acting as a balancer and supporter to the diesel engine.

This electric system size reduction is particularly pronounced in parallel hybrids, where the engine is directly connected to the load at all times, and thus only needs motors and batteries large enough to meet the difference in power between its chosen operating points and the load. This is in contrast to series hybrids, where the electric system is required to take the entire load and store a larger amount of energy, while also adding an extra component (the electric generator) to the engine unit.

1.2 This study and report

In this project, we will focus on excavators, as they are usually the main energy users, CO_2 emitters, and polluters on a job site. Volvo Construction Equipment (VCE) has developed diesel, series hybrid and BEV excavators, with either an electric motor drawing power from a lithium-ion battery and maintaining the speed of the hydraulic pump, and / or a diesel engine doing the same. There is now an interest in studying if hybridisation can be used to save fuel, downsize engines, and possibly, offer larger excavators (currently, the largest excavator sold is the 95-tonne EC950).

1.2.1 Focus on parallel hybrid instead of series hybrid

Volvo Construction equipment has previously explored series hybrid architecture as a hybrid solution for large excavators. The primary reason reason being the lack of mechanical coupling between the engine and the pump, which allows the engine to operate as a generator while the electric motor is used to hold the speed of the pump and handle the transients of the duty cycle. While this method enables simplified control of the drivetrain components, it introduces multiple energy conversion stages where the mechanical energy of the engine is converted into electrical energy and then back to mechanical energy at the hydraulic pump. These multiple conversion steps increase system losses, component size, weight, and cost.

Therefore, the method of hybridisation chosen to be studied in the thesis was the parallel hybrid architecture. This architecture reduces the losses due to energy conversion since both the engine and the electric machine can directly contribute torque to the drivetrain. In addition, the parallel architecture may allow downsizing of electrical components while maintaining acceptable performance and fuel economy.

However, the parallel hybrid introduces the challenge of maintaining the pump speed. Unlike the series hybrid, where the engine can operate independently, the parallel configuration requires careful coordination between mechanical and electrical power sources to achieve optimal performance and energy utilisation.

This thesis therefore focuses on evaluating the control strategies, energy management behaviour, and operational trade-offs associated with a parallel hybrid architecture.

1.2.2 Focus on engine downsizing

From literature, it is known that, without external power sources or recuperation strategies, the possibilities for fuel savings by hybridising to change the operating points are limited in those combustion engines where the efficiency map is relatively flat and where the fuel power almost completely linearly increases with shaft power, as is the case for the engines available for this study.[8] This was also confirmed from some quick initial simulations, where the addition of electric motors to take some of the load saved no fuel at all. In addition, adding electrical components to an existing engine directly adds new machine costs on top of the existing ones.

Therefore, to see real fuel savings, it is necessary to use engines smaller than the conventional ones. Hybridisation in this case becomes necessary mainly to help the smaller engine reach the power output of the larger one when the demand exceeds its own capability. Then, in the other regions, the engine either delivers the load or charges the battery more efficiently than the conventional engine would.

1.2.3 Research questions

- Can an excavator of a certain weight class be run by a smaller engine, assisted by electric motors to fulfil load demands that currently can only be met by larger engines, without draining the battery?
- How should the load be split between the combustion engine and electric motors in such an excavator to minimise fuel consumption?
- What is the resulting change in capital cost and running costs of the machine, and in what situations does hybridisation make economic sense?
- What other technologies and opportunities for energy saving does hybridisation enable?

1.2.4 Layout of this report

- The report starts with the discussion of theoretical concepts from literature and existing knowledge. First, the design of excavator powertrains and simulated powertrain components is discussed, followed by an exploration of various strategies to split the load power between the diesel and electric powertrains.
- These strategies are used to make controllers on Simulink, which are integrated with the powertrain models of excavators of two weight classes in a testbench.
- Then, the powertrain models are put through various simulated load cycles with these controllers, subject to operational requirements such as holding the hydraulic pump speed constant and returning the battery state of charge (SoC) to the starting value.
- The fuel consumption is measured and the savings between the algorithms compared. The flexibility and ease of implementation of the algorithms are also compared, both against the simulated conventional machine and the pre-existing data from the series study.
- A rough calculation about the potential for fuel savings with energy recovery technologies is also made. Finally, the change in the total cost of operation is calculated and discussed.

2
Theory

This section discusses excavators as systems, the setup of the parallel hybrid excavator simulation environment, and the component models used therein. The designs of the energy management control strategies have also been discussed in detail.

2.1 The excavator system

2.1.1 Conventional excavators

An excavator is principally composed of a body with a digging apparatus and a cab mounted on a chassis with either wheels or continuous tracks, such that the body can rotate horizontally. This project studied excavators with tracks, also called *band* or *crawler* excavators, as shown in Figure 2.1. The digging apparatus typically comprises a boom attached to the body, an arm attached to the boom, and a task-specific attachment (like a bucket or a claw) mounted at the end of the arm. These are operated by pumping pressurised fluid into or out of piston-cylinder actuators. The same pressurised fluid is also used to power the hydraulic motor that rotates the body, and in the case of crawler excavators, the hydraulic motors for the tracks as well.

Figure 2.1: A crawler excavator and its parts

All power from the combustion engine in a typical excavator is delivered to a master hydraulic pump, either by direct drive, via torque converter, or via a single gear reduction as shown in Figure 2.2. The pump pressurises hydraulic fluid, which is delivered based on driver input to the actuating systems named above via a control system comprised of various valves.

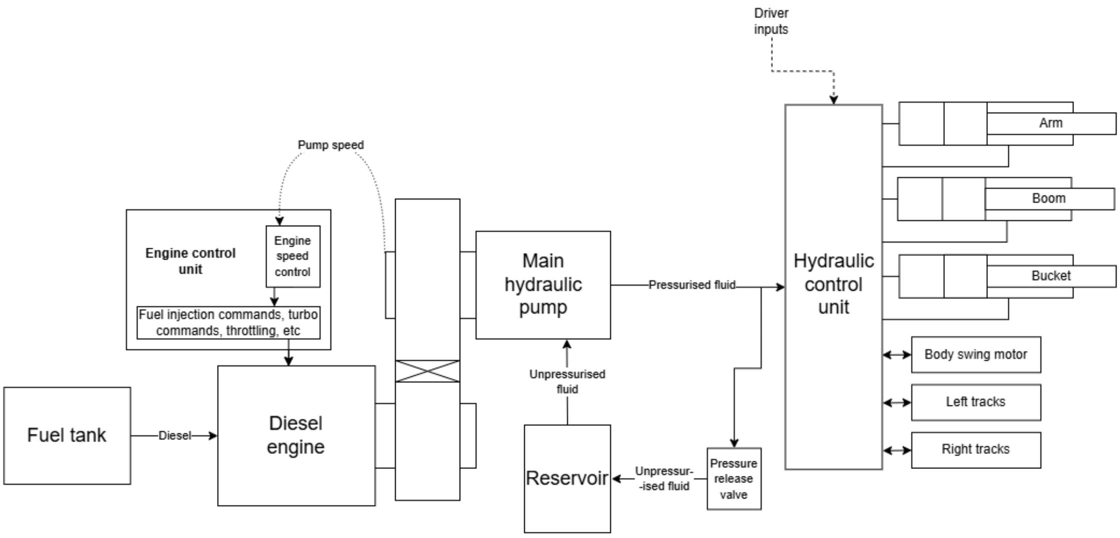


Figure 2.2: Architecture of a conventional diesel excavator with a central hydraulic pump driving pressurised fluid to all actuators

When there is a load increase on the actuators, the pressure in the hydraulic fluid lines increases, causing the pump to tend to slow down, and vice versa. The engine control of such an excavator principally involves ensuring that this pump operates at a constant speed, in order to maintain a constant hydraulic pressure, no matter what loads are imposed by the excavator's bucket, arm, swing, propulsion, etc.

In a fully-electric BEV excavator, the same role - of driving the pump and holding its speed constant - is played by an electric motor drawing power from a battery.

2.1.2 Powertrain control in excavators

Since the pump speed is to be held constant, the prime movers are required to respond to change in power demand P_{load} or torque demand T_{load} primarily by changing their torque in direct proportion. In other words, assuming no losses, if the pump and the prime movers spin at the speeds ω_{pump} and ω_{pm}, then the torque T_{pm} that the prime mover must deliver is

$$\begin{aligned} P_{load} &= P_{pm} \\ T_{load} * \omega_{load} &= T_{pm} * \omega_{pm} \\ T_{pm} &= T_{load} * \frac{\omega_{load}}{\omega_{pm}} = \frac{P_{load}}{\omega_{pm}} \end{aligned} \tag{2.1}$$

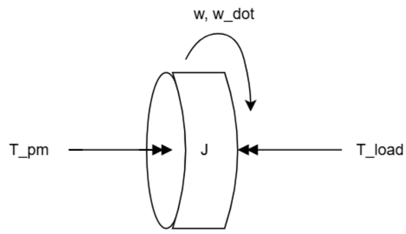


Figure 2.3: Lumped flywheel model of a powertrain

How this requirement of T_{pm} is responded to by the prime mover will determine the actual speed of the pump. Consider a simplified system as shown in Figure 2.3, where the rotational inertia of all components spinning at ω, driven by torque T_{pm} against load torque T_{load} is lumped together as J. The system behaves under the known relationship $T_{pm} - T_{load} = J * \dot{\omega}$, and thus, if T_{pm} is always equal to T_{load}, the pump will maintain a fixed speed. Commanding torque directly from the prime mover in this manner is hereafter referred to as *torque control*.

However, it is not always possible to sense changes in load torque immediately. Even if sensed, commanding torque from a prime mover always results in a delay in response, thus causing $\dot{\omega}$ above to be non-zero, i.e., causing the speed to increase or decrease. This means that to meet the power demand, the actual torque needed is slightly different from the T_{pm} that is delivered by the prime mover, by the inverse proportion of the change in speed. But since the prime mover in torque control is only aware of the torque request, it continues to deliver the same, causing a change in its actual power output $P_{pm} = T_{pm} * \omega_{pm}$, as its own speed is changing without its knowledge. This causes a further divergence between the needed and the commanded/delivered torque, resulting in a cascading loss in speed stability and possible machine failure.

To solve this issue, a method that adds a small corrective torque based on the difference between the required speed and the actual speed, referred to as *speed control*, is used. This error may be used as a control signal for P or PI controllers to produce a corrected torque demand in real time. With this method, the need for feeding the sensed load torque directly is also eliminated, since the system can react to minimise the speed error from the beginning, thus almost always following the load torque.

To summarise,

- In **torque control** mode, the prime mover is commanded to deliver a certain torque value, irrespective of its speed, which is influenced externally. The torque controller seeks to minimise the error between commanded and delivered torque.
- In **speed control** mode, the prime mover is commanded to maintain a certain speed, and deliver whatever torque is necessary to do so. The speed controller seeks to minimise the error between the commanded and actual output shaft speeds.

As shown in Figure 2.2, the signals from torque or speed controllers then go on to lower-level powertrain controls embedded with physical components, such as fuel injectors or airflow controllers in IC engines, stator/rotor current controllers in electric motors, and so on.

2.1.3 Hybrid excavators

The single powertrain of a conventional excavator can be supported by another powertrain using a different energy source, in which case it becomes a hybrid excavator. Apart from battery-driven electric power, technologies like hydraulic accumulators, hydrogen fuel cells, and electric accumulators have been used to hybridise excavators.

2.1.4 Energy management control

In hybrid excavators, if there are two prime movers, Equation 2.1 becomes

$$\begin{aligned} P_{load} &= P_{pm1} + P_{pm2} \\ T_{load} * \omega_{load} &= T_{pm1} * \omega_{pm1} + T_{pm2} * \omega_{pm2} \\ T_{pm1} &= \frac{T_{load} * \omega_{load} - T_{pm2} * \omega_{pm2}}{\omega_{pm1}} = \frac{P_{load} - P_{pm2}}{\omega_{pm1}} \end{aligned} \tag{2.2}$$

Deciding the split between what the power output of each prime mover should be, i.e., the split between P_{pm1} and P_{pm2}, directly decides how much the energy source for each prime mover - whether a fuel tank, a battery, or fluid in a pressure accumulator - is depleted or replenished. Thus, it is known as *energy management*, and the algorithms that decide this split in a machine in real time are designed to obey *energy management control strategies*. An important distinction is thus drawn between energy management control and powertrain control:

Energy management control	**Powertrain control**
Decides what torques and speeds to command from each prime mover in a powertrain with multiple prime movers to maximise efficiency.	Ensures that the demanded torque and speed is delivered by the prime mover by minimising signal errors and applying corrective torques.
Does not strictly need feedback from the prime movers.	Requires feedback of torque and/or speed signals from the prime movers.

Table 2.1: Difference between powertrain control and energy management control

2.1.5 Architecture of a parallel hybrid excavator

The simplest version of a parallel hybrid excavator is where both the diesel engine and electric motors are directly connected to the central hydraulic pump, either by direct drive or with fixed gear ratios.

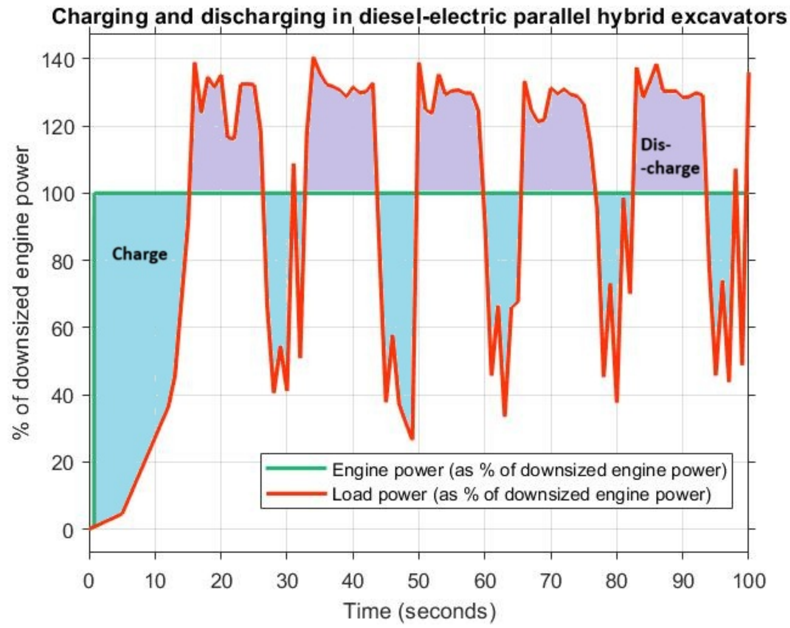


Figure 2.5: Battery charging and discharging in a parallel hybrid excavator.

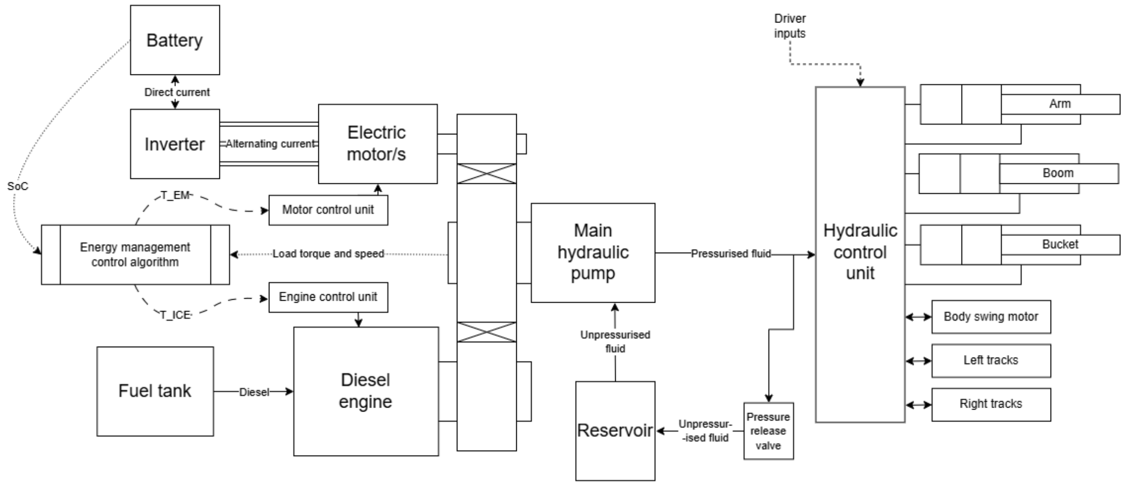


Figure 2.4: Architecture of a parallel hybrid diesel-electric excavator

In such a machine, the battery is charged or discharged based on the electric machine acting as a generator or motor respectively, as shown in Figure 2.5. The battery is charged when the machine acts as a generator to 'brake' the diesel engine when it generates more power than the load. Conversely, the battery is discharged when the machine acts as a motor to add power to the diesel engine when the engine generates less power than the load. Since there are no external sources for charging the battery, it is the engine power itself that needs to be modulated to maintain a consistent battery state of charge (SoC).

2.2 Modelling the powertrain

2.2.1 Forward simulation

To obtain a realistic understanding of the energy consumption and behaviour of the powertrain components under transient loading conditions, a forward-facing simulation approach is employed. In this approach, the operator demand is provided as an input to the system model, and the resulting system behaviour is calculated sequentially in time based on the physical dynamics of the powertrain components. In this study, the parallel hybrid excavator model was simulated in MATLAB/Simulink using the forward simulation approach, where the operator demand was represented by the torque request of the hydraulic pump. The energy management control algorithm determines the torque split between the internal combustion engine and the electric motor(s), following which each individual component calculates its respective energy consumption based on its mathematical model.
The key difference between the quasi-static and forward simulation approaches lies in their modelling principles. In a quasi-static approach, the system is assumed to operate in steady-state conditions, where transient dynamics and component interactions are neglected, and outputs are determined directly from predefined efficiency or performance maps. In contrast, the forward simulation approach captures the dynamic interactions between components as well as the effects of delays, rotational inertia, efficiency variations, and controller response over time. This enables a more realistic representation of the transient operating behaviour of the hybrid excavator powertrain.

2.2.2 Models of the engine and motor

The internal combustion engine used in the simulation model is represented using a dynamic forward-facing model that accounts for both the rotational inertia of the engine and its fuel consumption characteristics. The rotational dynamics of the engine are governed by

$$J_{ice}\dot{\omega}_{ice} = T_{ice} - T_{load} \tag{2.3}$$

where J_{ice} is the engine rotational inertia, ω_{ice} is the engine angular speed, T_{ice} is the engine output torque, and T_{load} is the load torque acting on the engine shaft.
The fuel consumption of the engine is calculated using efficiency maps based on the instantaneous engine operating point. The engine output power is given by

$$P_{ice} = T_{ice}\omega_{ice} \tag{2.4}$$

Using the engine efficiency obtained from the efficiency map, the fuel power is determined as

$$P_{fuel} = \frac{P_{ice}}{\eta_{ice}} \tag{2.5}$$

The corresponding fuel mass flow rate is then calculated as

$$\dot{m}_{fuel} = \frac{P_{fuel}}{Q_{LHV}} \tag{2.6}$$

where η_{ice} is the engine efficiency obtained from the map and Q_{LHV} is the lower heating value of the fuel.
The electric motor is similarly modelled as a dynamic component including rotor inertia effects. The motor rotational dynamics are expressed as

$$J_{em}\dot{\omega}_{em} = T_{em} - T_{load} \tag{2.7}$$

where J_{em} is the rotor inertia of the electric motor, ω_{em} is the motor speed, and T_{em} is the electromagnetic torque produced by the motor.
The mechanical power delivered by the motor is calculated as

$$P_{em} = T_{em}\omega_{em} \tag{2.8}$$

Motor losses are incorporated using efficiency characteristics obtained from the motor efficiency map. During motoring operation, the electrical power drawn from the battery is expressed as

$$P_{bat} = \frac{P_{em}}{\eta_{em}} \tag{2.9}$$

while during regenerative operation,

$$P_{bat} = P_{em}\eta_{em} \tag{2.10}$$

where η_{em} is the motor efficiency corresponding to the operating point.
The motor current is determined from the battery power and terminal voltage according to

$$I_{em} = \frac{P_{bat}}{V_{bat}} \tag{2.11}$$

where V_{bat} is the battery terminal voltage. This allows the model to capture the electrical energy consumption and regenerative charging behaviour of the hybrid powertrain system.

2.2.3 Battery model

The battery is modelled using an equivalent circuit approach consisting of an ideal voltage source and an internal resistance. The model captures the relationship between battery power, terminal voltage, current, and state of charge while maintaining low computational complexity suitable for system-level simulations.
The battery current is determined from the battery power demand according to

$$I_{bat} = \frac{V_{oc} - \sqrt{V_{oc}^2 - 4R_{int}P_{bat}}}{2R_{int}} \tag{2.12}$$

where V_{oc} is the open-circuit voltage, R_{int} is the internal resistance, and P_{bat} is the battery power.

The state of charge is updated using coulomb counting:

$$SoC(t + \Delta t) = SoC(t) - \frac{I_{bat}\Delta t}{Q_{bat}} \tag{2.13}$$

where Q_{bat} is the battery capacity expressed in Coulombs.
Positive battery power corresponds to battery discharge, while negative battery power represents regenerative charging. The battery model includes upper and lower state of charge limits to prevent overcharging and deep discharge. These limits are enforced within the supervisory controller during energy management optimisation.

2.3 Energy management control strategies

A variety of strategies have been used in past studies to split the load power between prime movers in hybrid vehicles. Notable amongst these are dynamic programming (DP), equivalent consumption minimisation strategies (ECMS), and rules-based methods. [10].

2.3.1 Dynamic Programming

Dynamic programming is used as a global optimisation technique for the energy management of hybrid electric vehicles. It is based on Bellman's principle of optimality which states that if a trajectory that connects an initial point and a final point by the utilisation of a cost function, then the sub-trajectory, connecting any intermediate point to the same terminal point must also be optimal [12]. Therefore the optimal solution to a decision making problem can be constructed from the optimal solutions of its sub-problems.
For the parallel hybrid system considered in this study, the objective of the dynamic program is to minimise the fuel consumption as follows:

$$\beta = \sum_{k=1}^{N-1} \dot{m}_{fuel}(k)\,\Delta t + \lambda\,(SoC_N - SoC_{\text{target}})^2 \tag{2.14}$$

where $\dot{m}_{fuel}$ is the fuel mass flow rate (kg/s), Δt is the time step, SoC_N is the final state of charge, SoC_{target} is the desired terminal SoC, and λ is a weighting factor penalising deviation from the target SoC.

The optimisation is subject to the following constraints:
Engine torque limits:

$$T_{\text{ice \_min}} \leq T_{\text{ice}} \leq T_{\text{ice\_max}}(\omega_{ice}) \tag{2.15}$$

T_{ice_max} is a function of the speed at which the engine is running (ω_{ice})
Motor torque limits:

$$T_{\text{em\_min}} \leq T_{\text{em}} \leq T_{\text{em\_max}} \tag{2.16}$$

State of charge bounds:

$$SoC_{\text{min}} \leq SoC \leq SoC_{\text{max}} \tag{2.17}$$

Dynamic programming obtains the optimal solution based on the knowledge of the entire drive cycle, including the driver torque demand sand the vehicle speed. Both the state variable (Battery State of Charge (SoC)) and the control variable (Engine Torque (T_{ice})) are discretised into finite grids of admissible values.

The solution is obtained through a backward recursive process. Starting from the final time step, a terminal cost is assigned based on the deviation of the SoC from a desired target value. The algorithm then proceeds backward in time, evaluating all possible control actions for each discretised SoC state at every time step. For each candidate control input, the corresponding electric motor torque is computed using the drivetrain torque balance, and the feasibility of the resulting operating point is verified against system constraints such as torque limits, efficiency bounds, and SoC limits.

For feasible control actions, the instantaneous cost, defined as the fuel consumption over the time step, is calculated. The battery power is estimated using the electric motor efficiency map, and the next SoC state is determined using the system dynamics. The future cost associated with this next state is obtained through interpolation of the cost-to-go function computed in the subsequent time step. The total cost is then formed as the sum of the instantaneous cost and the future cost.

Among all candidate control inputs, the one that minimises the total cost is selected as the optimal control action for the given state and time step. This process is repeated for all states and time steps, resulting in a complete optimal control map stored as a function of SoC and time. This is referred to as the 'Backward Simulation' and the algorithm is described in the Figure 2.6.

It is then followed by the 'Forward Simulation' which applies the pre-computed optimal control map to generate the actual system trajectories over the drive cycle. Beginning from an initial State of Charge, the algorithm progresses forward in time, at each step identifying the nearest discretised SoC value in the grid and retrieving the corresponding optimal engine torque from the stored control map. The electric motor torque is then determined from the drivetrain torque balance, and the battery power is estimated using the electric motor efficiency map. The SoC at the subsequent time step is computed from coulomb counting and clamped within the admissible bounds.

Dynamic Programming provides a globally optimal solution for the given drive cycle and system model. However, its computational complexity increases significantly with the resolution of the state and control discretisation. The time complexity for a typical drive cycle of 1hr and a time step of 1s is given by $O(N \cdot Ns \cdot Nu)$, where Ns and Nu are the resolutions of the SoC and engine torque grid respectively. Considering a cycle of 3600s, a SoC grid of 31 grid points and a engine torque grid of 8 points, the overall number of iterations are $89.2e^3$, making it unsuitable for real-time implementation. Nevertheless, it serves as a valuable benchmark for evaluating suboptimal control strategies.

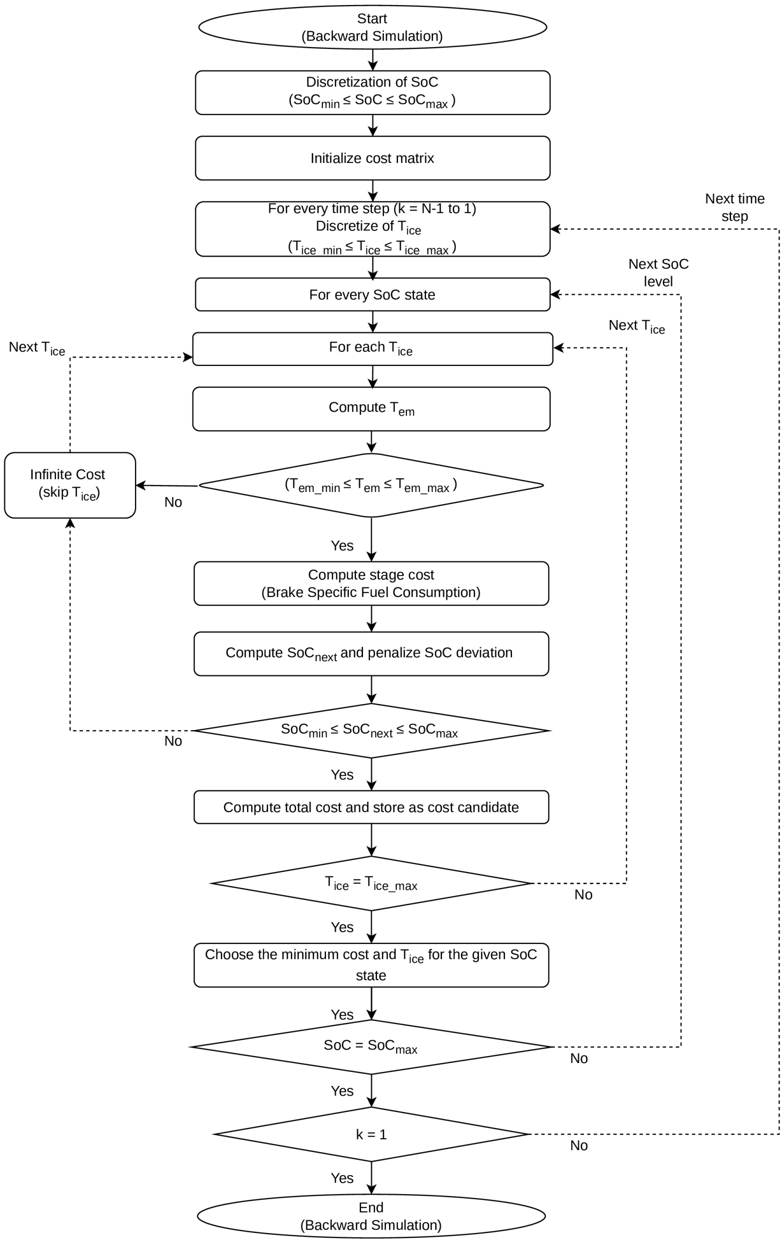


Figure 2.6: Dynamic Programming - Backward Simulation

2.3.2 Equivalent Consumption Minimisation Strategy

The Equivalent Consumption Minimisation Strategy (ECMS) is a widely used real-time energy management strategy for hybrid electric vehicles. The objective of ECMS is to determine the optimal instantaneous power split between the internal combustion engine and the electric machine such that the total equivalent fuel consumption is minimised while maintaining the battery state of charge (SoC) within acceptable limits. The method is based on Pontryagin's Minimum Principle (PMP),

where electrical energy consumption is converted into an equivalent fuel consumption using an equivalence factor [11].
For a given driving cycle, the total vehicle power demand P_{veh} is supplied by a combination of engine power and battery power. The instantaneous optimisation problem can be formulated using the cost function

$$\beta = \int_{t_0}^{t_f} \left(\dot{m}_{fuel}(x,u) + \dot{m}_{batt}(x,u)\right) dt \tag{2.18}$$

where $\dot{m}_{fuel}$ represents the engine fuel consumption rate and $\dot{m}_{batt}$ represents the equivalent fuel consumption associated with battery power usage. The state variable x corresponds to the battery SoC, while the control variable u represents the engine torque command.
Using PMP, the constrained optimisation problem can be transformed into minimisation of the Hamiltonian function. A detailed derivation of the PMP formulation and the corresponding co-state equations can be found in [13]. The resulting Hamiltonian is expressed as

$$H = \dot{m}_{fuel} + \frac{S(t)}{Q_{LHV}} P_{bat} \tag{2.19}$$

where P_{bat} is the battery power, Q_{LHV} is the lower heating value of the fuel, and $S(t)$ is the equivalence factor used to convert electrical energy into an equivalent fuel quantity.
The equivalence factor is dependent on the operating mode of the battery and is given by [13]

$$S(t) = \begin{cases} S_{chg} = \dfrac{\bar{\eta}_{em\_drive}\bar{\eta}_{B\_dis}}{\bar{\eta}_e} & P_{bat} > 0 \\ S_{dis} = \bar{\eta}_{em\_gen}\bar{\eta}_{B\_chg}\bar{\eta}_e & P_{bat} \leq 0 \end{cases} \tag{2.20}$$

where $\bar{\eta}_{em\_drive}$, $\bar{\eta}_{em\_gen}$, $\bar{\eta}_{B\_chg}$, and $\bar{\eta}_{B\_dis}$ represent the average efficiencies of the motor and battery during charging and discharging operation.
The battery power is determined from the electric machine power according to

$$P_{bat} = \begin{cases} P_{em}\eta_{em\_drive}\eta_{B\_chg} & \text{charging mode} \\ \dfrac{P_{em}}{\eta_{em\_drive}\eta_{B\_dis}} & \text{discharging mode} \end{cases} \tag{2.21}$$

In the case of an ideal battery both η_B and $\bar{\eta}_B$ are considered to be 1. The ECMS controller minimises the Hamiltonian at each simulation time step to obtain the optimal torque split between the engine and the electric machine. In the present study, the strategy implemented in MATLAB/Simulink for real-time evaluation of the power distribution in the parallel hybrid powertrain configuration is described in subsections 2.3.2.1 and 2.3.2.2.

2.3.2.1 Approximate ECMS

Although the conventional ECMS formulation provides near-optimal fuel economy, the instantaneous minimisation of the Hamiltonian can become computationally intensive for real-time implementation. To reduce the computational complexity, an approximate ECMS formulation based on polynomial approximation of the engine fuel consumption map is adopted from [13].
For a given engine speed, the engine fuel consumption rate can be approximated as a quadratic function of engine torque:

$$\dot{m}_{fuel} = a(\omega_{ice})T_{req}^2 + b(\omega_{ice})T_{req} + c(\omega_{ice}) \tag{2.22}$$

where $a(\omega_{ice})$, $b(\omega_{ice})$, and $c(\omega_{ice})$ are speed-dependent fitting coefficients obtained from the engine BSFC map and T_{req} is the requested torque from the engine.
By introducing a power allocation factor k_p, the equivalent fuel consumption function can be expressed as a cubic polynomial of the form

$$f(k_p) = Ak_p^3 + Bk_p^2 + Ck_p + D \tag{2.23}$$

where the coefficients A, B, C, and D are functions of the engine operating point and equivalence factor. Detailed derivation of the polynomial formulation and candidate solution selection procedure can be found in [13].
The Hamiltonian is then evaluated as

$$H(T_{ice}) = \dot{m}_{fuel}(T_{ice}) + \frac{S}{Q_{LHV}}P_{bat}(T_{ice}) \tag{2.24}$$

subject to the torque balance constraint

$$T_{em} = T_{load} - T_{ice} \tag{2.25}$$

At each simulation time step, the controller evaluates a finite set of admissible power allocation candidates and selects the operating point corresponding to the minimum Hamiltonian value. This approximation significantly reduces computational burden while maintaining near-optimal fuel economy performance.

2.3.2.2 Adaptive ECMS

The performance of ECMS strongly depends on the choice of equivalence factor S. A constant equivalence factor may lead to charge depletion or excessive battery charging under varying driving conditions. Therefore, an adaptive ECMS strategy is employed in this work to dynamically regulate the equivalence factor based on the deviation of the battery SoC from a desired target value.
The adaptive equivalence factor is expressed as

$$S(t) = S_0 + K_s(SoC_{tar} - SoC(t)) + I_{term}(t) \tag{2.26}$$

where S_0 is the nominal equivalence factor, K_s is the proportional gain, and $I(t)$ is the integral correction term given by

$$I_{term}(t) = \int_0^t K_i(SoC_{tar} - SoC(\tau))d\tau \tag{2.27}$$

The adaptive formulation introduces a feedback mechanism that continuously adjusts the battery usage penalty according to the SoC deviation. An increase in $S(t)$ penalises battery discharge and promotes engine operation, whereas a decrease in $S(t)$ favours electric propulsion. This enables charge-sustaining operation without requiring prior knowledge of the future driving cycle. A schematic representation of the implemented ECMS strategy is shown in Figure 2.7.

2.3.3 Rules-based energy management control

Rules-based strategies can be defined as if-then-else conditions, usually designed for specific conditions or duty cycles based on the specialised expertise and foreknowledge of engineers. They allow manual setting of the torques of the prime movers at specific operating points. At its simplest, a rules-based strategy for a parallel hybrid excavator with, say, three engine operating points, can be expressed as:

$$T_{ice} = f(t) = \begin{cases} x, & t < a \\ y, & a \leq t \leq b \\ z, & t > b \end{cases}$$

$$T_{em} = \frac{P_{load} - (T_{ice} * \omega_{ice})}{\omega_{em}}$$

where x, y, and z are torque values and t is any state variable of choice fulfilling the given conditions between arbitrary limits a and b. This open-ended nature leaves the design of the control entirely to the engineer's own creativity and thus a wide variety of formal and informal approaches exist.

Based on the state variable used for control (equivalent to t in the above example), Hoang Thai Do at Volvo Construction Equipment investigated two strategies for wheel loaders with parallel hybrid hydraulic accumulators.[10] One was *working moment-based* and the other was *power- and torque-based.* With the accumulator subject to upper and lower pressure limits in both cases, they can be summarised as follows

- **Working moment-based:** The accumulator was charged only from regenerative energy when available, and discharged upon reception of a specific signal from the machine (based on driver input).
- **Torque- and speed-based:** The accumulator was charged both from regenerative energy as well as directly from the engine whenever the load power was low and the engine could efficiently provide more. It was discharged if the required load torque was higher than what the engine could provide or higher than the desired operating point the engineer wished for the engine to run at.

Both strategies yielded good results that could match dynamic programming with proper tuning.

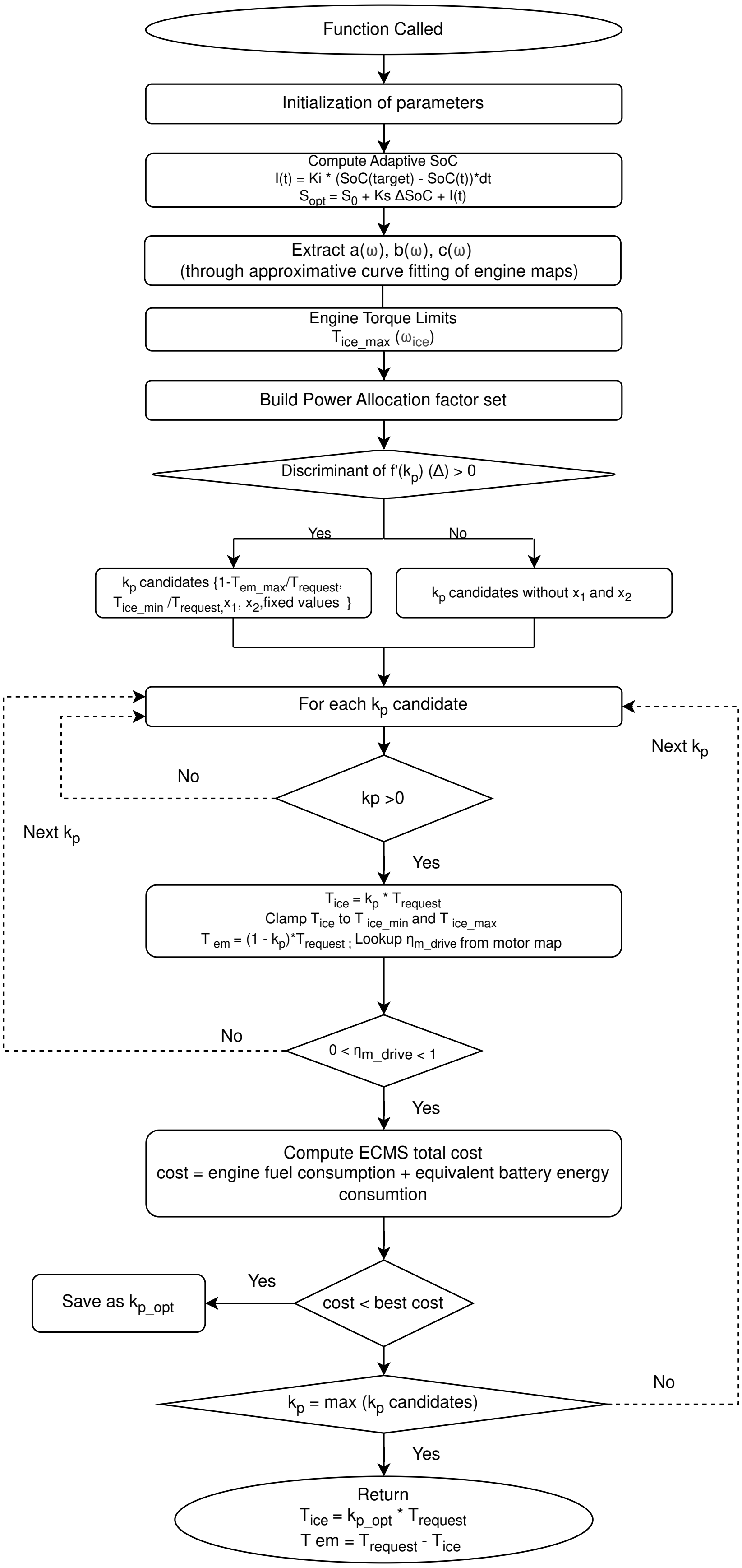


Figure 2.7: Schematic Overview of the ECMS Algorithm

In a diesel-electric hybrid excavator, the equivalent of the hydraulic accumulator would be the battery, and of the amount of pressurised fluid, the amount of charge in the battery (State of Charge, SoC). The equivalent of hydraulic pressure would be the battery voltage, but since batteries are much more energy-dense and power-dense than hydraulic accumulators, it would make more sense to use the SoC (which also affects the voltage) as an equivalent control variable. In contrast with wheel loaders, regenerative energy is generally not available in crawler excavators (except if equipped with specialised equipment, as discussed later, which are still not capable of charging a lithium-ion battery sufficiently in the same way as a hydraulic accumulator). Therefore, for this study, the torque- and speed-based approach is used as inspiration.

Lin, Pan, and Wang investigated the use of a similar approach for a diesel-electric parallel hybrid excavator, using SoC as the state variable for control.[9] For the 30kW engine, four operating points of specific torques and speeds were set in the most efficient operating regions of the engine, such that it produced power outputs of 12.7 kW, 17.2 kW, 19.1 kW, and 25.1 kW. If the selected operating point was higher than the average load power, the battery would (on average, but not at every instant) be charged by using the electric motor as a brake, and the SoC would rise. When the SoC reached an upper limit, the engine would be switched to the next lower-power operating point. Conversely, if the operating point was not powerful enough, the motor would add torque (on average) to the engine's output and thus discharge the battery, and the rising SoC would cause the engine to be switched to the next higher-power operating point.

As described in subsection 3.3.3, a modified version of these approaches is used, subject to the specific requirements of the machine in this study.

3
Methods

The following chapter focuses on the setup of the parallel hybrid excavator model in a simulation environment, implementation of energy management strategies on various drive cycles that depict the different operating conditions and load requirements. Lastly, the performance evaluation criteria used to compare the strategies will be introduced.

3.1 Configuration of the parallel hybrid simulation testbench

The prime movers of the diesel-electric parallel hybrid machine were simulated using Volvo's Global Simulation Platform on Simulink. The lumped flywheel approach described in Figure 2.3 was used to simulate the load on the powertrain from the pump. The gear ratio between the powertrains was designed such that the electric motors and the diesel engine would run at the speed at which they reach their peak power at their peak torque output - speeds which, coincidentally for both, also included a large part of the respective high-efficiency regions. The output torque of the powertrain on the pump shaft was calculated as the sum of the products of the individually generated torques of the machines and the gear ratios between the machine and the pump shaft, as described in Equation 2.2.

3.1.1 Choice of powertrain control

Two electric motors were used in this parallel hybrid, in addition to the diesel engine. This was in order to be able to re-use parts from Volvo's existing battery-electric version of the excavator, which uses two electric motors connected to the pump. This means that, with three prime movers, there were now twelve possible combinations of speed and torque control. One limitation is that exactly one of the prime movers should be in speed control, since having none will cause the speed to deviate from the target, and having more than one will cause them to 'fight' each other as they react to each other changing the speed error, physically connected as they are to each other at all times. It was noted that this choice of powertrain control, although insignificant in terms of fuel savings, strongly affected the ability to hold pump speed constant. Thus, the most capable combination - using the diesel engine and one motor in torque control, and the other motor in speed control - was fixed and used for all further studies.

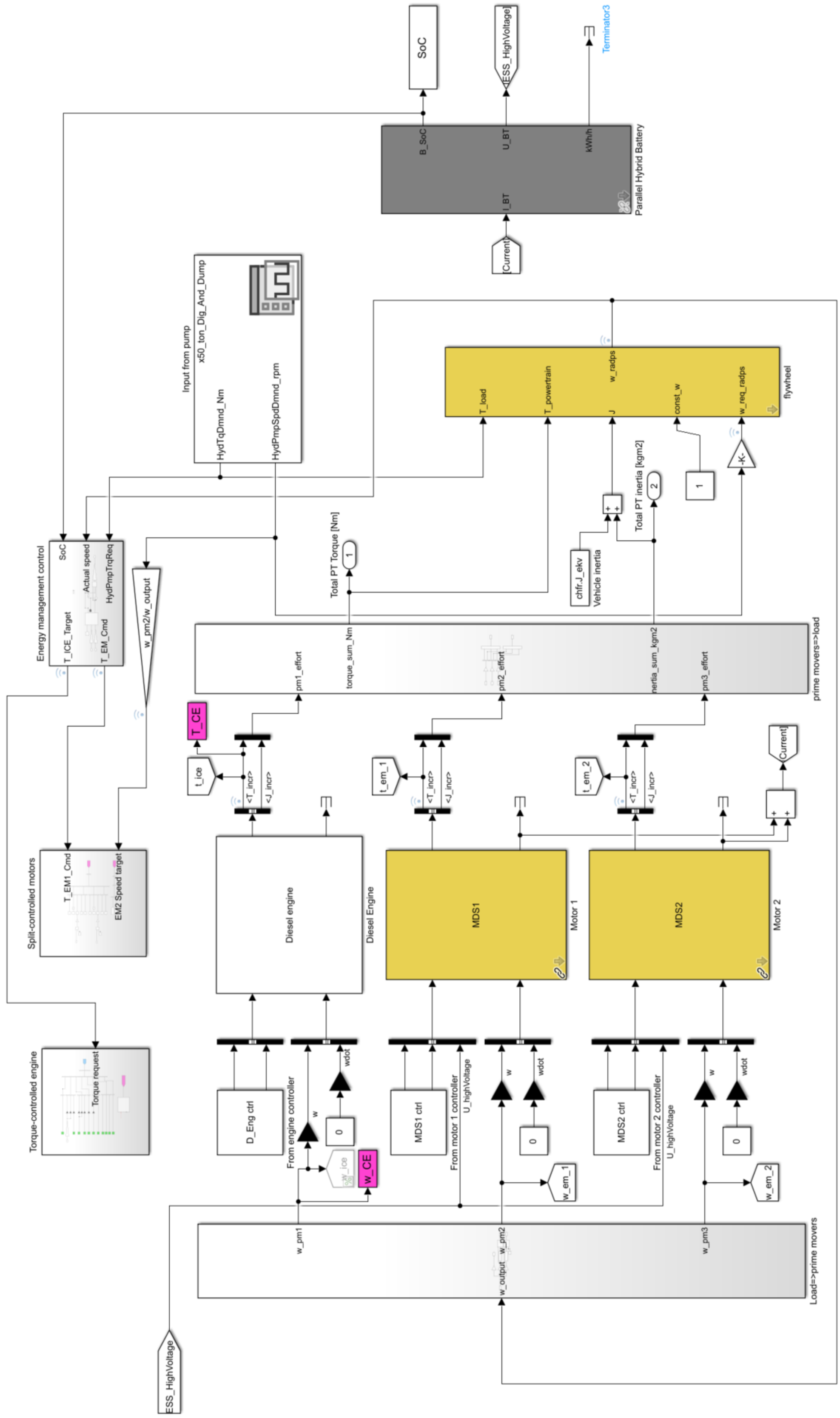


Figure 3.1: Simulation environment of the parallel hybrid excavator powertrain.

3.2 Duty cycles of the excavators

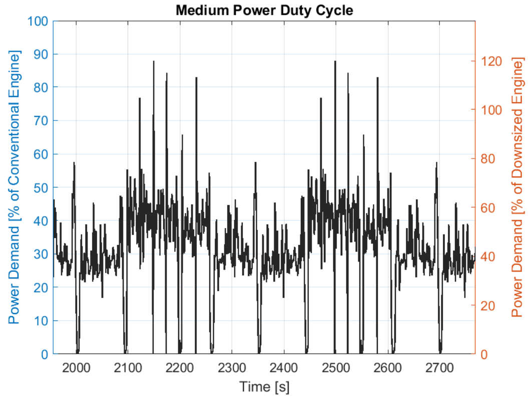
Excavators belonging to two weight classes were analysed in this study. The 75-tonne excavator is expected to largely operate under highly intense duty cycles. The 50-tonne excavator, being a more versatile medium-duty construction machine, is expected to operate under a wide range of working conditions. Apart from idling periods, the operating conditions of the excavator can broadly be classified into three categories based on the nature and intensity of the operation.

- **Grading Operations:** During grading operations, the excavator bucket is primarily used to scrape and level the ground or loose piled material without significant scooping or lifting actions. These operations are characterised by relatively low hydraulic and traction power demand and therefore represent the least power-intensive active operating condition.
- **Travelling Operations:** Travelling operations involve manoeuvring the excavator around the worksite using the caterpillar tracks. The power demand during travelling is moderately high and varies depending on factors such as vehicle speed, terrain gradient, and payload conditions.
- **Dig-and-Dump Operations:** Dig-and-dump operations represent the primary excavation task, where the excavator bucket is used to dislodge and scoop material, followed by lifting the arm and boom, swinging the upper structure, and dumping the material into a container or dump truck. The average and peak power requirements during these operations depend on the excavated material, operating speed, and elevation difference between the digging and dumping locations. These cycles generally correspond to the most power-intensive operating condition of the excavator.

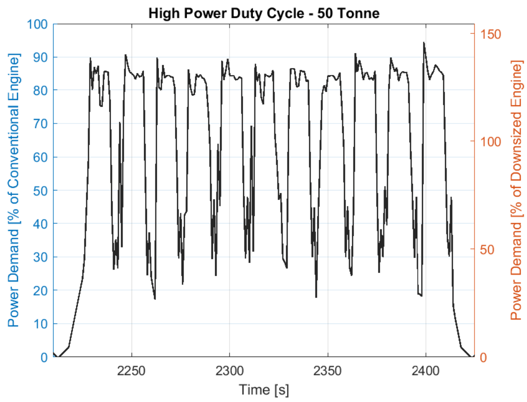
Figure 3.2: Examples of excavator operations. The two upper images show a grading action and the two lower images show a dig-and-dump action.

Different combinations of the above operating conditions were used to generate representative excavator duty cycles for evaluating the performance of the considered energy management strategies. The developed duty cycles are summarised below.

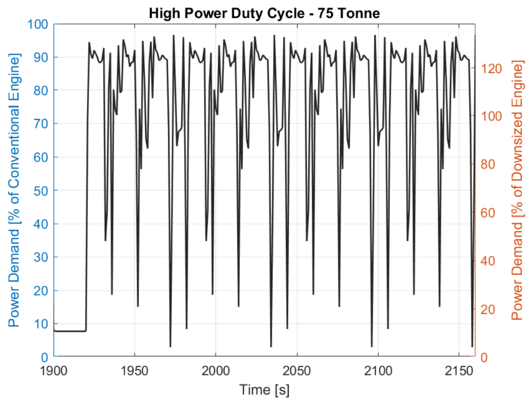
(a) Low Power Cycle



(b) Medium Power Cycle



(c) High Power Cycle - 50 Tonne



(d) High Power Cycle - 75 Tonne

Figure 3.3: Normalised power demand for different duty cycle snippets represented as a percentage of conventional and downsized engine power ratings.

- **Low Power Cycle:** This duty cycle represents grading and idling operations of the 50-tonne excavator. The average and peak power demand during this cycle lie approximately between 3% and 5% of the maximum engine power of the conventional excavator. The duration of the cycle is 3437 s.
- **Medium Power Cycle:** This duty cycle represents travelling operations of the 50-tonne excavator. The average power demand during the cycle is approximately 30% of the maximum engine power, while the peak power demand reaches nearly 87%. The duration of the cycle is 3489 s.
- **High Power Cycle – 50-tonne Excavator:** The high-power cycle primarily consists of repeated dig-and-dump operations separated by short idling intervals. The duration of this cycle is 3689 s. The average power demand during this cycle lies between 50% and 60% of the maximum engine power, with peak power demand reaching approximately 95%.
- **High Power Cycle – 75-tonne Excavator:** This cycle is similar in nature to the high-power cycle developed for the 50-tonne excavator but represents the operating characteristics of a larger 75-tonne machine. The average and peak

power demands correspond to approximately 65% and 85% of the maximum engine power respectively. The duration of the cycle is 3600 s.

Selected snippets of the duty cycle are presented in Figure 4.1, where the power demand is normalised with respect to the rated power of both the conventional and downsized engines.

3.3 Implementation of Energy Management Strategies

The energy management strategies described in Chapter 2 were subjected to continuous improvements to achieve the least possible fuel consumption, while maintaining battery State of Charge by the end of each duty cycle.

3.3.1 Implementation of DP

Dynamic Programming (DP) was implemented offline for the excavator drive cycles described previously. The state variable (battery State of Charge (SoC)), and the control variable (the engine torque), were discretised into 31 and 8 grid points respectively. The selected grid resolution provided a compromise between computational effort and solution accuracy. The method of engine torque grid selection has been further discussed in subsection 3.3.1.1. The discretised values were defined within the operating constraints described in Section 2.3.1.

The optimisation was carried out using a backward recursive approach with a simulation time step of 1 s. At each time step, all feasible control actions were evaluated subject to the system constraints, including engine torque limits, electric motor torque limits, and SoC bounds. Since the objective of the DP implementation was energy management optimisation at the supervisory control level, the fast inertial dynamics of the prime movers were neglected. Similarly, the battery SoC evolution was estimated using the coulomb counting method without incorporating detailed battery dynamic modelling.

Following the backward optimisation process, a forward simulation was performed to reconstruct the optimal state and control trajectories over the complete drive cycle. During implementation, the weighting factor λ in the cost function was separated into two tunable penalty terms. The first term penalised the deviation of the final SoC from the target SoC value, while the second term penalised intermediate SoC deviations during the drive cycle in order to prevent excessive charging or discharging of the battery.

The optimal trajectories obtained from the DP algorithm were subsequently applied to the simulation test bench environment. Since the DP optimisation was performed with a time step of 1 s, the resulting trajectories were interpolated to match the simulation test bench sampling time of 0.01 s. These interpolated trajectories acted as the energy management controller by providing the optimal torque split at each simulation instant. The resulting operating trajectories were then used to evaluate the fuel consumption and overall system performance of the hybrid excavator.

3.3.1.1 Sensitivity Study on Engine Torque Grid Resolution

A sensitivity study was conducted to investigate the influence of engine torque grid resolution on the fuel consumption obtained from the Dynamic Programming (DP) optimisation. The study was performed using the high-power excavator drive cycle with a duration of 3689 s, while maintaining the SoC discretisation fixed at 31 grid points. The engine torque discretisation was varied from 4 to 20 grid points in increments of 4.

The objective of this study was to evaluate the trade-off between optimisation accuracy and computational complexity. Since the computational complexity of the DP algorithm scales according to $O(N \cdot N_s \cdot N_u)$, increasing the number of engine torque grid points directly increases the number of control candidates evaluated during the backward recursive optimisation process.

Table 3.1: Sensitivity study on engine torque grid resolution

Engine Torque Grid Points (N_u)	Fuel Consumption [L]	Big-O Complexity
4	47.2406	$O(N \cdot N_s \cdot 4)$
8	47.2401	$O(N \cdot N_s \cdot 8)$
12	47.2046	$O(N \cdot N_s \cdot 12)$
16	47.1730	$O(N \cdot N_s \cdot 16)$
20	47.1561	$O(N \cdot N_s \cdot 20)$

The results indicate that increasing the engine torque grid resolution improves the optimisation result only marginally. Increasing the resolution from 4 to 20 grid points reduced the fuel consumption by approximately 0.0845 L over the complete drive cycle. However, this improvement was achieved at the expense of a fivefold increase in the number of control candidates evaluated during the optimisation process.

Therefore, beyond a certain discretisation resolution, the reduction in fuel consumption becomes relatively small compared to the increase in computational burden. Based on this trade-off between optimisation accuracy and computational efficiency, an engine torque discretisation of 8 grid points was selected for the remainder of this study.

3.3.2 Implementation of ECMS

Unlike Dynamic Programming, which was implemented as an offline global optimisation strategy, the Equivalent Consumption Minimisation Strategy (ECMS) was implemented online such that the optimal torque split was determined instantaneously at each simulation time step of 0.01s. The objective of the ECMS controller was to minimise the equivalent fuel consumption by optimally distributing the power demand between the internal combustion engine and the electric machine.

The implementation of the ECMS algorithm required the engine and electric motor efficiency maps described in Section 2.2. In order to improve computational efficiency, approximate fitted curves of the engine brake specific fuel consumption (BSFC) map were extracted and stored separately from the simulation environment. This reduced the computational overhead associated with repeatedly querying the complete engine map during runtime. In practical implementation, the optimisation process is subject to physical operating constraints including engine torque limits, motor torque limits, battery operating limits, and efficiency variations of the electric machine. The optimisation is therefore performed over a constrained set of admissible control inputs to ensure physically feasible operation.

The performance of the ECMS algorithm is highly dependent on the equivalence factor $S(t)$, referred to in the implementation as S_{opt}. The instantaneous equivalence factor was derived from a nominal equivalence factor S_0, which was tuned to achieve a balanced utilisation of the engine and electric machine while maintaining acceptable battery State of Charge (SoC) behaviour and minimising fuel consumption.

To regulate deviations of the SoC from the target value, proportional and integral correction terms were incorporated into the equivalence factor adaptation mechanism. The proportional gain K_s was used to provide immediate correction of SoC deviations during the drive cycle, thereby preventing excessive charging or discharging of the battery. The integral gain K_i was employed to reduce long-term cumulative SoC deviations and maintain charge sustenance over the complete drive cycle.

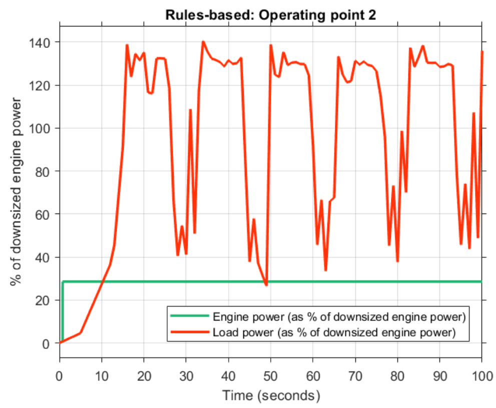
The tuning of the proportional and integral gains significantly influenced the dynamic behaviour of the energy management strategy. Excessively large proportional gains resulted in aggressive corrections in the torque allocation between the prime movers, producing undesirable fluctuations in pump and engine operating speeds. Conversely, low proportional gains led to delayed corrective action and gradual battery depletion. Similarly, excessively high integral gains caused large cumulative corrections over time, whereas low integral gains resulted in persistent steady-state deviations of the SoC from the target value. Therefore, the controller gains were tuned iteratively until acceptable SoC trajectories and smooth torque trajectories of the prime movers were obtained.

Furthermore, the candidate set of power allocation factors evaluated by the ECMS controller was constrained based on the operating capability of the internal combustion engine and the power requirements of the excavator duty cycle. Since the computational complexity of the ECMS algorithm depends on the number of candidate power allocation factors evaluated at each time step, the computational burden could be further reduced by limiting the admissible operating range or reducing the resolution of the candidate set.

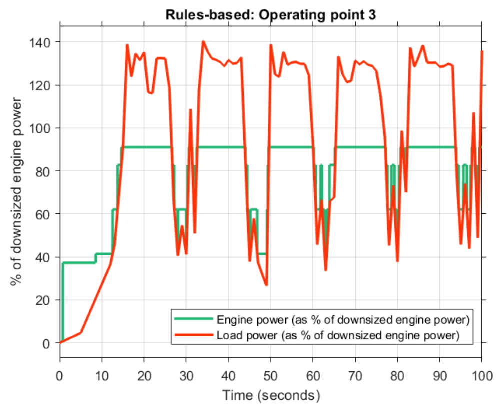
3.3.3 Implementation of the rules-based strategy

The implementation of the rules-based strategy started out with the ideas developed by Lin, Pan & Wang [9] discussed in the previous section, with the limitation that all chosen operating points would be at the same speed. Thus, the only variable that needs to be set is the torque T_{ice} of the engine, with the electric motors providing the remaining torque. The first version of this rules-based algorithm was designed with one low-power, one high-power, and one switch-off mode. In the switch-off mode, fuel injection to the engine is stopped, and the motors thus have to overcome the friction torque of the engine in addition to the usual load from the pump.

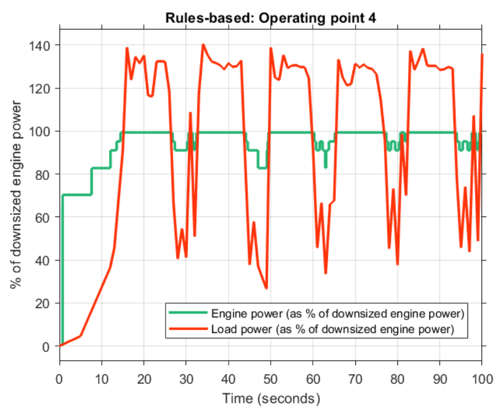
During the course of fine-tuning these levels, it was found to be advantageous to have intermediate modes between the low- and high-power modes that also loosely followed the trajectory of the load torque itself. This prevented the situation of SoC breakpoints being the only way to modulate the power of the engine, allowing for the engine to fewer changes in operating point, as well as a smaller battery SoC window usage



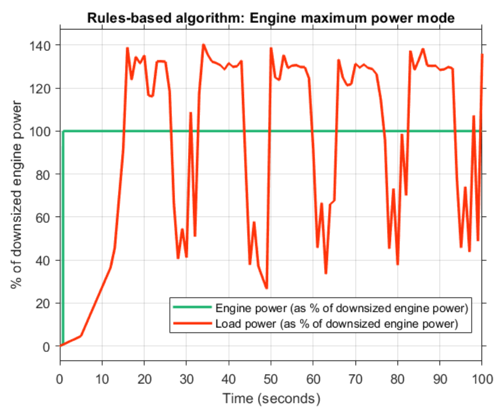
(a) Low power operating point



(b) Lower intermediate operating point



(c) Higher intermediate operating point



(d) Maximum power operating point

Figure 3.4: The four operating points of the rules-based algorithm where the engine is running. At operating point 1, the engine is switched off.

within medium-power operations. As shown in Figure 3.4, two such intermediate modes are proposed, one with higher average power than the other, for use when SoC is slightly lower. In all, the logic of the rules-based algorithm is as in Figure 3.5.

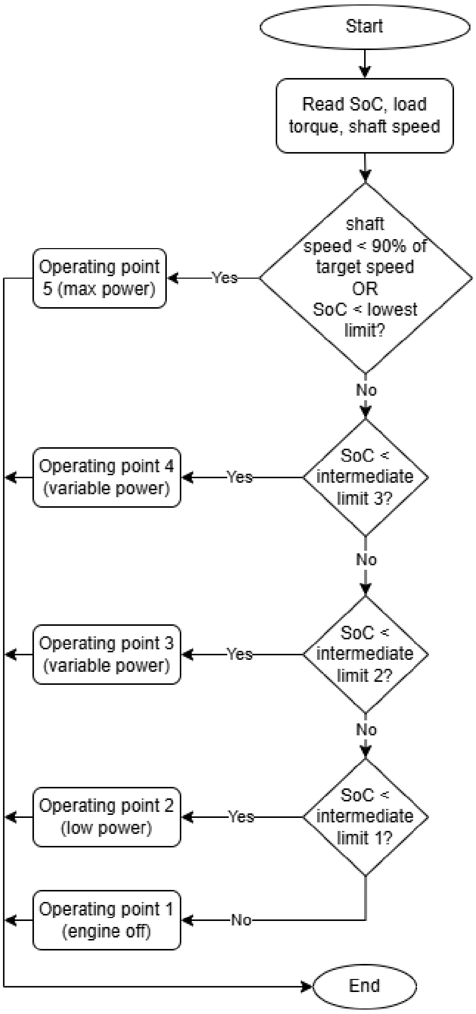


Figure 3.5: Logical flowchart of the rules-based strategy at each time step.

3.3.4 Performance evaluation

The implemented energy management strategies were evaluated and compared based on multiple performance criteria in order to assess not only their fuel-saving potential, but also their computational efficiency and practical applicability for real-world excavator operation. The evaluation framework considered the following aspects:

- **Fuel Consumption Reduction:** Since the primary objective of this study is to reduce fuel consumption, the total fuel consumed over each duty cycle was considered as the principal performance metric. The fuel-saving potential of each energy management strategy was evaluated by comparing the obtained fuel consumption values under identical operating conditions.
- **State of Charge Sustenance:** In addition to fuel consumption, the battery

State of Charge (SoC) trajectory was monitored to ensure charge-sustaining operation. Excessive battery depletion or overcharging during the duty cycle indicates impractical power management behaviour and therefore must be avoided. The deviation of the final SoC from the target SoC was consequently used as an additional performance indicator.

- **Computational Complexity:** The computational complexity associated with each algorithm was evaluated in terms of the number of computations required during optimisation and control execution. The complexity of the algorithms was analysed using Big-O notation in order to assess their relative computational burden and scalability with increasing state and control discretisation.
- **Real-Time Feasibility:** The practical applicability of the considered energy management strategies was assessed based on their suitability for online implementation in real-world excavator applications. Particular emphasis was placed on determining whether the algorithms could operate in real time under realistic computational constraints.
- **Scalability and Adaptability:** The scalability of the algorithms was evaluated based on the number of tunable parameters, sensitivity to operating conditions, and the extent of modifications required for implementation across different duty cycles and excavator classes. Algorithms requiring extensive retuning or manual parameter adjustment for varying operating conditions were considered less scalable for practical deployment.

3.4 Operational cost analysis

Since it was of interest to understand the economic feasibility of the hybrid solution, a Total Cost of Operation (TCO) study was conducted. The two relevant components of TCO are the cost of the machine itself, and how much it costs to run the machine over time.

In this project, the machine costs of interest were calculated as the sums of only those powertrain components which would face changes during the process of hybridisation. The rest of the machine components were assumed to remain unchanged, so they would not affect the cost calculation. Since the exact values of these costs are classified, they were instead calculated as a percentage of $\$_{mach}$, the cost of the conventional powertrain.

The operational costs of interest were only the fuel costs over time, since they are the only ones affected by this hybridisation exercise. Since the battery is intended to be charged by the engine itself by expending fuel, without external charging, electrical costs are not relevant. The cost of maintenance is assumed to remain the same due to the high reliability of the added electrical components compared to the diesel engine.

To calculate the fuel costs of the machine for such an overarching cost analysis, one must analyse the fuel savings in an averaged duty cycle that represents how long customers as a whole are expected to use the machine in the different task-specific duty cycles presented in section 3.2.

3.4.1 Population-representative duty cycle

A five-hour composite duty cycle was developed by combining the different excavator operations to represent a typical full working day of the 50-tonne excavator. The cycle composition consisted of approximately 25% grading operations, 50% dig-and-dump operations, 10% travelling operations, and 15% idling periods. This cycle was primarily used for evaluating the long-term performance and feasibility of the selected energy management strategy under realistic operating conditions.

3.4.2 Battery sizing

Battery sizing involves choosing the number of cells to put in series and the number of such strings in parallel to meet design requirements. The number of cells in series was decided based on the voltage requirements of the inverter V_{req} as:

$$n_{series} = \frac{V_{req}}{V_{oc}} \tag{3.1}$$

where V_{oc} is the open circuit voltage of an individual lithium-ion cell. The number of strings in parallel was decided based on the maximum current demand of the motor I_{max} and the allowable SoC window such that:

$$n_{parallel} = \frac{I_{max}}{I_{lim}} * \frac{100}{\text{Maximum SoC \%} - \text{Minimum SoC \%}} \tag{3.2}$$

where I_{lim} is the maximum charge or discharge current that an individual cell can safely withstand.

3.4.3 Fuel cost calculation

The average workday for the excavator was assumed as 8 hours, and it is expected to run for 250 days per year. Thus, for a certain fuel volume consumption rate $\dot{V}_{fuel}$ in litres per hour over a period of t years, the annual cost of fuel can be given as

$$\$_{fuel} = \dot{V}_{fuel} * 8 * 250 * \$_L \tag{3.3}$$

where $\$_L$ represents the cost of one litre of fuel. The resultant costs are normalised to the cost of the conventional powertrain $\$_{mach}$ for the sake of confidentiality.

3.4.4 Breakeven time

The breakeven time represents the duration required for the additional investment associated with the hybrid powertrain to be recovered through the reduction in annual fuel costs. It provides an indication of the economic feasibility of the hybrid solution over long-term operation. The breakeven time was calculated as

$$t_{even} = \frac{\text{Excess in machine cost}}{\text{Value of fuel saved per year}} \tag{3.4}$$

4

Results

4.1 Verification of pump speed and SoC stability

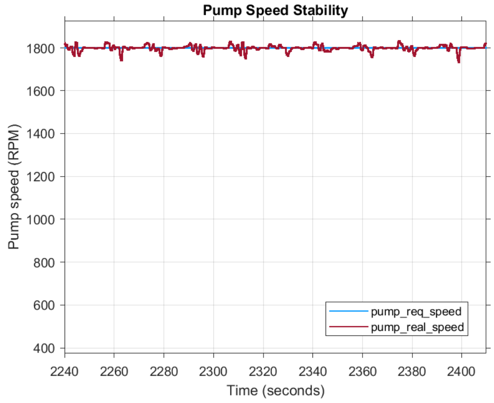
Before evaluating the performance of the different energy management control strategies, the stability of the hydraulic pump speed and the battery state of charge (SoC) behaviour were verified. Since the excavator hydraulic system requires the pump to operate at an approximately constant speed to maintain stable hydraulic pressure, excessive deviations in pump speed indicate inadequate powertrain control performance.

Figures 4.1a and 4.1b compare stable and unstable pump speed behaviour respectively. In the stable case, the pump speed closely tracks the reference operating speed with a standard deviation and root mean square error (RMSE) of approximately 9.52 RPM, while the maximum peak error remains limited to 155.01 RPM. This indicates that the combined engine and motor torque response is capable of compensating for transient load variations while maintaining stable hydraulic operation.

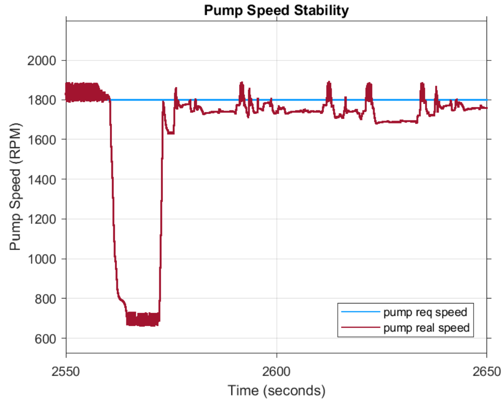
In contrast, the unstable case exhibits significant oscillations and poor speed regulation, resulting in a standard deviation of 283.23 RPM, an RMSE of 285.26 RPM, and a peak deviation exceeding 1522 RPM. The unstable deviations are a result of improper configuration of the powertrain control. Such behaviour is undesirable since large pump speed fluctuations can negatively affect hydraulic performance, drivability, and component durability.

The stability of the battery state of charge was similarly evaluated over a representative duty cycle segment of approximately 200 s, as shown in Figures 4.1c and 4.1d. In the acceptable case, the SoC remains nearly charge sustaining, varying only from 49.06% to 49.07%. Since the analysed segment is repeatedly encountered within the complete duty cycle, maintaining a near-constant SoC over the segment indicates that the battery charge balance will remain stable over long-term operation.

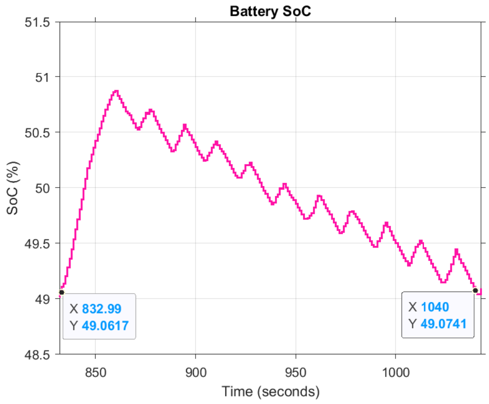
Conversely, the unacceptable SoC behaviour demonstrates a continuous net battery discharge, where the SoC decreases from 58.05% to 57.47% over the same segment duration. Although the reduction appears small within a single segment, repeated operation over the full duty cycle would result in progressive battery depletion. Therefore, maintaining charge-sustaining behaviour is essential for ensuring sustainable long-term hybrid operation without excessive battery discharge or overcharging.



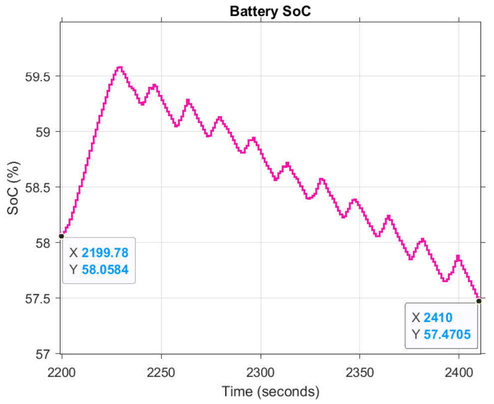
(a) Stable Pump Speed Behaviour



(b) Unstable Pump Speed Behaviour



(c) Stable SoC Behaviour



(d) Unstable SoC Behaviour

Figure 4.1: Acceptable and unacceptable behaviour of the pump and battery SoC

4.2 Fuel consumption and savings

The fuel consumption performance of the parallel hybrid excavator was evaluated for multiple duty cycles representing low, medium, and high load operating conditions. The obtained fuel consumption values were compared against the corresponding conventional excavator configurations in order to quantify the effectiveness of the implemented energy management strategies. The results are presented both in terms of percentage of final consumption and percentage of instantaneous consumption relative to the conventional machine.

4.2.1 50-tonne machine

4.2.1.1 High load cycles

For the high-load duty cycle of the 50-tonne excavator, all investigated control strategies produced relatively small fuel savings compared to the conventional machine. Dynamic Programming achieved the lowest fuel consumption, corresponding to approximately 98.51% of the conventional fuel consumption, while the ECMS and rules-based strategies obtained values of 98.53% and 98.98% respectively. This corresponds to fuel savings of approximately 1.49%, 1.47%, and 1.02%.

The limited fuel savings observed during the high-load duty cycle can be attributed to the consistently high power demand imposed on the downsized engine. Under such operating conditions, the engine operates for a significant portion of the cycle within the high torque region, which typically corresponds to a relatively efficient operating range of the engine.

As a result, the potential benefit of hybridisation becomes limited, since there are fewer opportunities for the electric machine to improve the overall operating efficiency of the powertrain. In addition, the severity of the duty cycle requires the electric machine to provide sustained high power assistance, thereby restricting the flexibility of the energy management strategy and limiting the achievable reduction in fuel consumption.

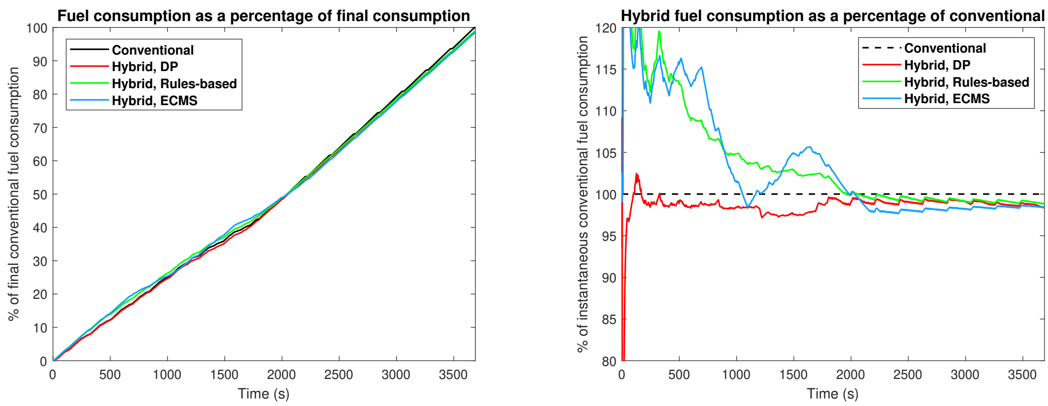


Figure 4.2: Fuel consumption of the 50-tonne machine in the high-load duty cycle

4.2.1.2 Medium load cycles

For the medium-load duty cycle, all three energy management strategies achieved noticeable fuel savings compared to the conventional excavator configuration. The hybrid configurations consumed approximately 91.7% − 94.1% of the conventional fuel consumption, corresponding to savings close to 8.3% − 5.9%.

Compared to the high-load cycle, the medium-load cycle provided greater opportunities for efficient hybrid operation. The lower average load demand enabled the electric machine to assist the engine more effectively during transient load variations.

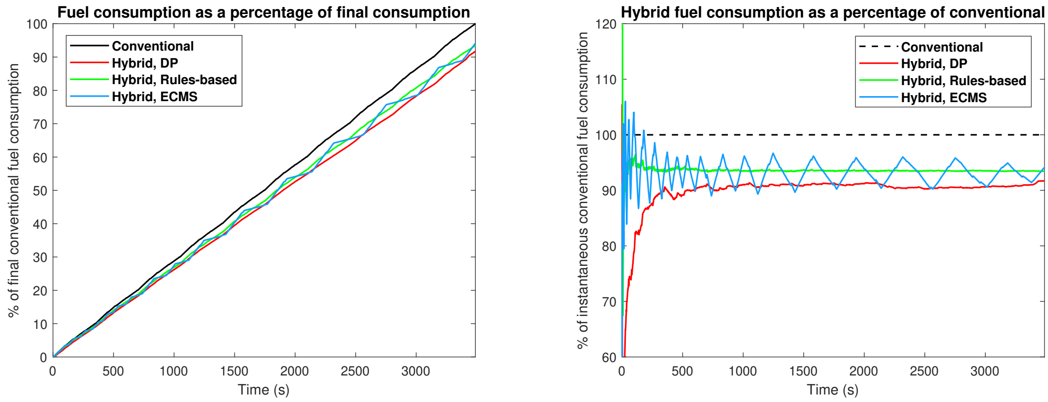


Figure 4.3: Fuel consumption of the 50-tonne machine in the medium-load duty cycle

4.2.1.3 Low load cycles

The largest relative fuel savings were obtained during the low-load duty cycle. Dynamic Programming and ECMS achieved fuel consumption values of approximately 43.94% and 45.58% relative to the conventional machine, while the rules-based strategy consumed approximately 52.59%.

Under low-load operating conditions, the hybrid system benefits from increased opportunities for electric assistance. Since the demanded power remains relatively low, the electric machine can support a larger proportion of the load demand without rapidly depleting the battery. Additionally, the downsized engine can avoid inefficient low-load operation more effectively, resulting in improved overall fuel economy.

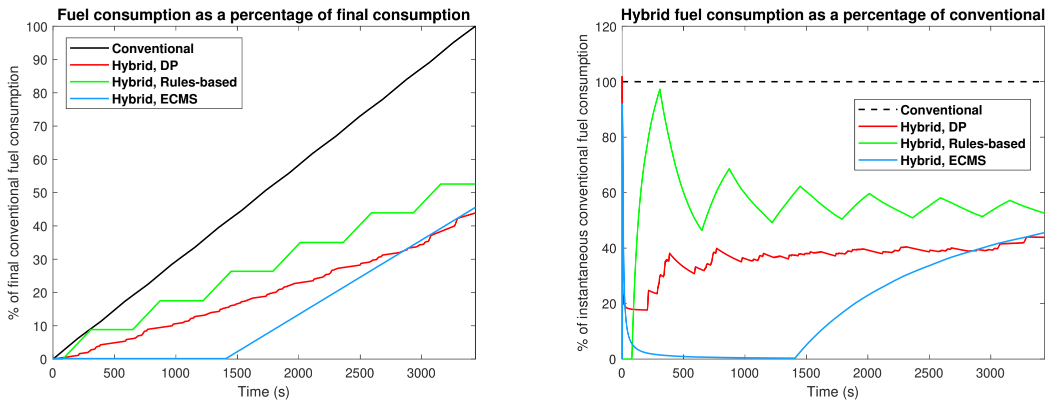


Figure 4.4: Fuel consumption of the 50-tonne machine in the low-load duty cycle

4.2.2 75-tonne machine

The 75-tonne excavator configuration when simulated for a high power duty cycle demonstrated similar overall trends to the 50-tonne machine. Dynamic Programming again achieved the lowest fuel consumption, followed by the rules-based

controller and ECMS. The hybrid configurations consumed approximately 97.1% – 98.0% of the conventional fuel consumption, corresponding to a maximum fuel savings between of 2.89%.
Compared to the 50-tonne machine, the larger excavator operated under consistently higher load conditions, reducing the relative contribution of the electric machine to the total power demand. Consequently, the achievable fuel savings remained limited despite the implementation of hybridisation and engine downsizing.

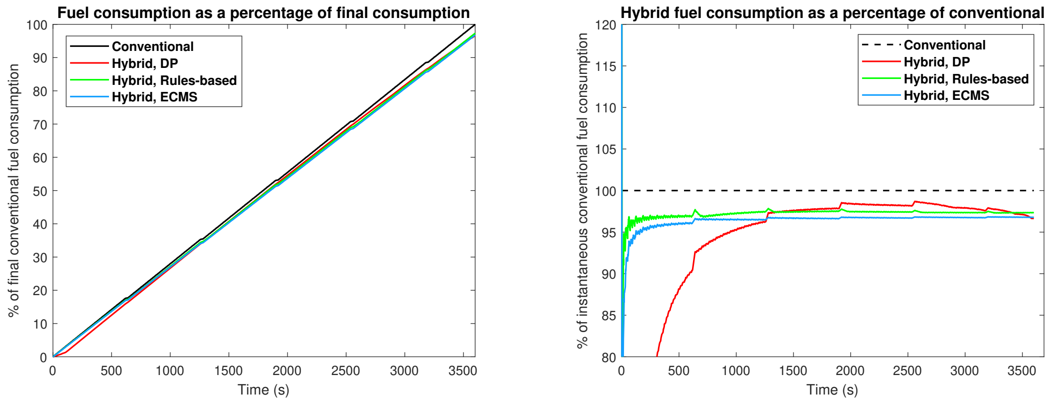


Figure 4.5: Fuel consumption of the 75-tonne machine in its duty cycle

4.2.3 Summary

Overall, the simulation results demonstrate that the parallel hybrid excavator configuration with a downsized engine achieved measurable fuel consumption reductions across all investigated duty cycles and machine configurations. Dynamic Programming consistently provided the globally optimal solution, while the rules-based and ECMS controllers achieved near-optimal real-time performance.
These observations suggest that parallel hybridisation is particularly beneficial for excavator duty cycles characterised by transient and moderate load operation, with diminishing returns for continuously high-load applications. Greater fuel savings were achieved during low and medium load cycles, where the downsized engine could operate efficiently in regions where the conventional engine would be highly inefficient, with the motor absorbing the transient torques. In contrast, high-load cycles provided limited opportunities for fuel savings since the conventional engine consistently operated near its efficient region. The percentage of fuel savings per cycle has been summarised in Table 4.1.

Table 4.1: Percentage fuel consumption savings relative to the conventional excavator

Drive Cycle	DP	Rules-based	ECMS
Low Power Cycle	56.06%	47.41%	54.42%
Medium Power Cycle	8.27%	6.54%	5.93%
High Power Cycle - 50 Tonne	1.49%	1.02%	1.47%
High Power Cycle - 75 Tonne	2.89%	2.67%	2.78%

4.3 Algorithm Recommendation Based on Performance Evaluation

Based on the performance evaluation criteria defined in Section 3.3.4, the rules-based energy management strategy is recommended as the most suitable real-time control strategy for the considered parallel hybrid excavator application.

Dynamic Programming (DP) consistently provided the globally optimal solution for all investigated duty cycles, as expected from an offline optimisation method with complete future cycle knowledge. However, among the real-time implementable strategies, the rules-based controller generally achieved fuel consumption values close to the DP benchmark and the ECMS controller.

This behaviour can be attributed to the repetitive and predictable nature of the excavator duty cycles considered in this study. The heuristic torque split rules were able to maintain the engine within favourable operating regions while effectively utilising electric assistance. In contrast, the ECMS controller relied heavily on the tuning of the equivalence factor, making its performance more sensitive to operating conditions and parameter calibration. Although the ECMS results remained close to those of the rules-based strategy, small deviations in tuning could lead to suboptimal battery utilisation and engine operating behaviour. The tracking behaviour of each algorithm for engine torque and motor torque can be seen in Appendix 1 Figure A.1 and Figure A.2. The battery SoC trajectories for each algorithm is represented for a repeating segment from the high power cycle in Figure A.3.

The rules-based strategy also demonstrated stable charge-sustaining behaviour across the investigated duty cycles while still achieving near-optimal fuel consumption. In terms of computational complexity and real-time feasibility, the rules-based controller offered a clear practical advantage since it relied primarily on predefined logical conditions and gain scheduling without requiring online optimisation. DP exhibited the highest computational burden and therefore served mainly as an offline benchmark, while ECMS provided a compromise between optimisation performance and computational cost.

The scalability and adaptability analysis further favoured the rules-based approach. When transitioning from the 50 tonne excavator configuration to the 75 tonne configuration, the ECMS controller required significant retuning due to changes in engine efficiency maps, fitted polynomial approximations, and equivalence factor calibration. In contrast, the rules-based controller required comparatively limited retuning, particularly for engines with similar operating characteristics and relatively flat high-efficiency regions.

Overall, although DP provided the theoretical optimum solution and ECMS demonstrated near-optimal real-time performance, the rules-based strategy offered the most favourable balance between fuel consumption reduction, SoC sustenance, computational simplicity, real-time feasibility, and scalability for the considered excavator application.

4.4 Total cost of operation: 50-tonne machine

The 50-tonne machine was run through the population-representative duty cycle with the recommended rules-based algorithm.

4.4.1 Combined fuel savings

The selected energy management strategy was evaluated using the population-representative duty cycle described in Section 3.4.1. The results showed that the hybrid powertrain consumed only 92.85% of the fuel required by the conventional powertrain over the five-hour cycle, corresponding to a fuel consumption reduction of 7.15%.

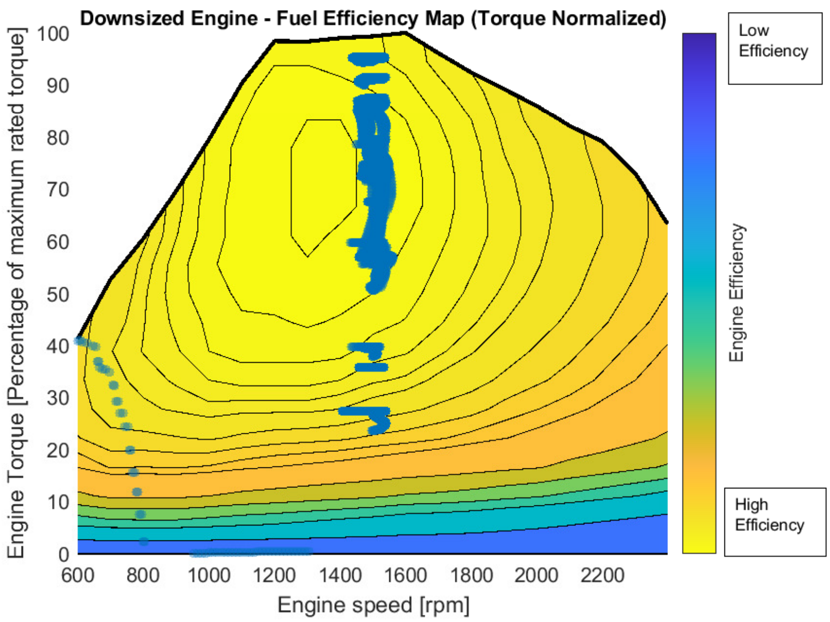


Figure 4.6: Operating points of the engine for the population representative cycle.

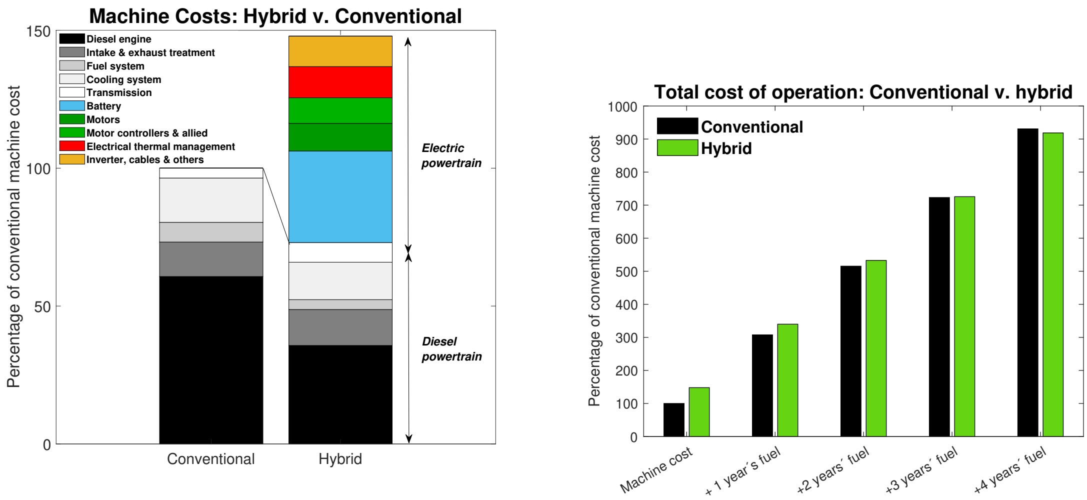
This result indicates that the hybrid architecture is capable of achieving meaningful fuel savings under realistic operating conditions representative of a full working day. The reduction in fuel consumption was achieved primarily through maintaining the engine at its most efficient operating points and switching it off when not necessary, as shown in Figure 4.6, which shows the engine operating point distribution over the engine efficiency map for the population-representative duty cycle.

4.4.2 Machine costs, running costs, and breakeven

Under the process of hybridisation, the downsizing of the engine allows for a cost reduction of 27% on the diesel powertrain components. However, this cost saving is erased by the addition of the electrical powertrain components, of which half the added cost is the lithium-ion battery and its cooling system alone. The total cost of the hybrid powertrain is 47% greater than that of the diesel powertrain, and this excess should be compensated by the fuel savings in a reasonable amount of time. The annual cost of fuel for the conventional machine is calculated using the approach in Equation 3.3 to be 207.8% of the machine cost; therefore, an 7.15% savings in fuel, as indicated by the powertrain with the rules-based algorithm operating over the combined cycle, translates to an annual fuel consumption by the hybrid that is $(1 - 0.0715) * 2.078 = 192.94\%$ of the cost of the conventional powertrain. The breakeven time in years is thus:

$$
\begin{aligned}
t_{even} &= \frac{\text{Excess in machine cost}}{\text{Value of fuel saved per year}} = \frac{(1.47 - 1) * \$_{machine}}{(2.07 - 1.929) * \$_{machine}} \\
&= \frac{0.47}{0.141} = 3.33 \approx 3 \text{ years } 4 \text{ months}
\end{aligned}
\tag{4.1}
$$

Assuming the full added cost of the hybrid powertrain is passed to the customer, the customer begins to see cost savings from this particular hybrid machine versus its conventional counterpart after three years and four months of use, as seen in Figure 4.7b.



(a) Machine costs

(b) Total cost of operation

Figure 4.7: Machine and fuel costs influencing the total cost of operation.

5

Conclusions and Discussions

5.1 Conclusions

This thesis investigated the feasibility of a parallel hybrid hydraulic excavator equipped with a downsized diesel engine and electrical energy storage system. Multiple energy management strategies, including Dynamic Programming (DP), Equivalent Consumption Minimization Strategy (ECMS), and a rules-based controller, were evaluated under representative excavator duty cycles for both 50-tonne and 75-tonne machine configurations.

The simulation results demonstrated that the hybrid powertrain was capable of achieving measurable fuel consumption reductions across all investigated operating conditions while maintaining stable hydraulic pump speed and charge-sustaining battery behaviour. The hybrid configuration achieved the largest relative fuel savings during low-load operation, where reductions exceeding 50% were obtained for the optimal and near-optimal strategies. Medium-load cycles resulted in moderate savings of approximately $6\% - 8\%$, while high-load cycles produced comparatively limited reductions of approximately $1\% - 3\%$. For the population-representative five-hour duty cycle, the selected rules-based controller achieved an overall fuel consumption reduction of approximately 7.15% relative to the conventional excavator.

The results further showed that the effectiveness of hybridisation strongly depends on the operating characteristics of the excavator duty cycle. Under transient and moderate load conditions, the electric machine was able to support a significant portion of the demanded power, allowing the downsized engine to avoid inefficient operating regions. However, during sustained high-load operation, the conventional engine already operated close to its efficient region, thereby limiting the achievable benefit of hybrid assistance.

The rules-based controller demonstrated the most favourable balance between fuel consumption reduction, computational simplicity, robustness, and scalability between machine sizes, making it the most practical solution for the considered application.

Although the obtained fuel savings demonstrate the technical feasibility of parallel hybridisation for hydraulic excavators, the economic analysis revealed a more challenging perspective. The introduction of the electrical powertrain components increased the overall powertrain cost significantly, resulting in a breakeven period of approximately three years and four months despite the achieved fuel savings. From a manufacturer and customer perspective, such a payback period may limit the attractiveness of the investigated hybrid architecture, particularly considering the additional system complexity and investment cost associated with electrification.

The results therefore suggest that engine downsizing and hybridisation alone may not be sufficient to provide the level of fuel savings required for strong economic competitiveness in heavy excavator applications. To further improve the viability of hybrid excavators, additional energy-saving technologies must be investigated. One particularly promising direction is the introduction of energy recuperation systems within the hydraulic machine. Previous studies have shown that hydraulic and kinetic energy recuperation can provide substantially larger reductions in fuel consumption by recovering energy that would otherwise be dissipated during machine operation. Integrating such recuperation technologies with the investigated parallel hybrid architecture could significantly improve both the fuel economy and the economic attractiveness of future hybrid excavators.

Overall, this thesis demonstrates that parallel hybridisation can successfully reduce fuel consumption and improve engine operating efficiency in hydraulic excavators. However, for large-scale industrial adoption, future developments should focus not only on hybrid powertrain optimisation but also on incorporating advanced energy recuperation strategies capable of delivering greater overall efficiency improvements and shorter economic payback periods.

5.2 Scope for future work

The present study can be extended in several directions to further improve the performance and applicability of hybrid excavator energy management systems. Some potential areas for future work are outlined below:

- **Investigation of energy recuperation potential:** Previous studies in the literature indicate that energy recuperation can further improve the overall energy efficiency of hybrid construction machinery. Incorporating and evaluating recuperation strategies within the simulation framework would provide a better understanding of the achievable energy savings under different excavator operating conditions. Such analyses could assist in quantifying the practical benefits of regenerative systems and support future industrial implementation of hybrid excavator technologies.
- **Detailed battery modelling and battery sizing:** In the present work, the battery model and sizing approach were intentionally simplified in order to focus primarily on the evaluation of the hybrid powertrain architecture and the energy management strategies. Consequently, the battery behaviour can be considered close to ideal compared to real-world operating conditions. Future work could therefore focus on the implementation of more detailed battery models incorporating factors such as battery ageing, thermal behaviour, charge-discharge efficiency variations, and chemistry-dependent characteris-

tics. In addition, further studies could investigate optimal battery sizing for heavy-duty excavator applications using commercially available battery technologies. Such analyses would provide a more realistic assessment of system durability, lifecycle performance, packaging constraints, and the economic feasibility of hybrid excavator powertrains.

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A

Appendix 1

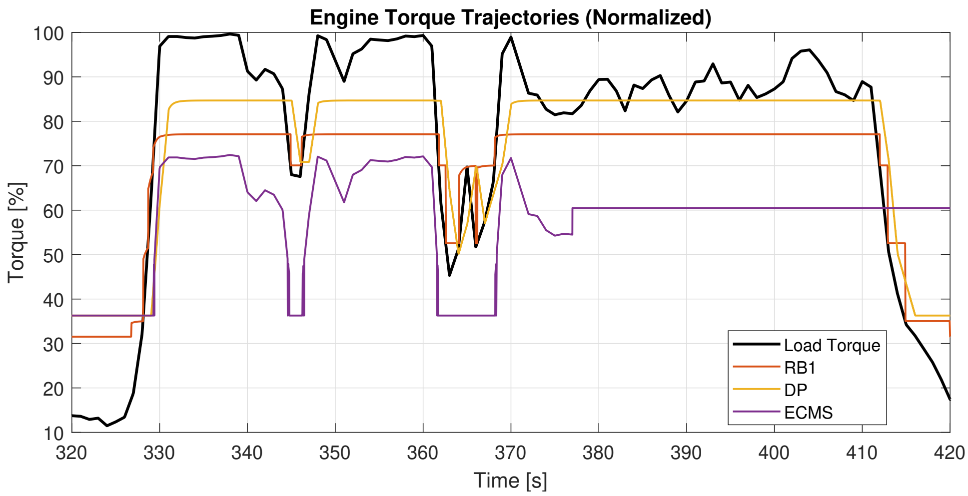

Figure A.1: Engine torque trajectories tracking comparison for all algorithms.

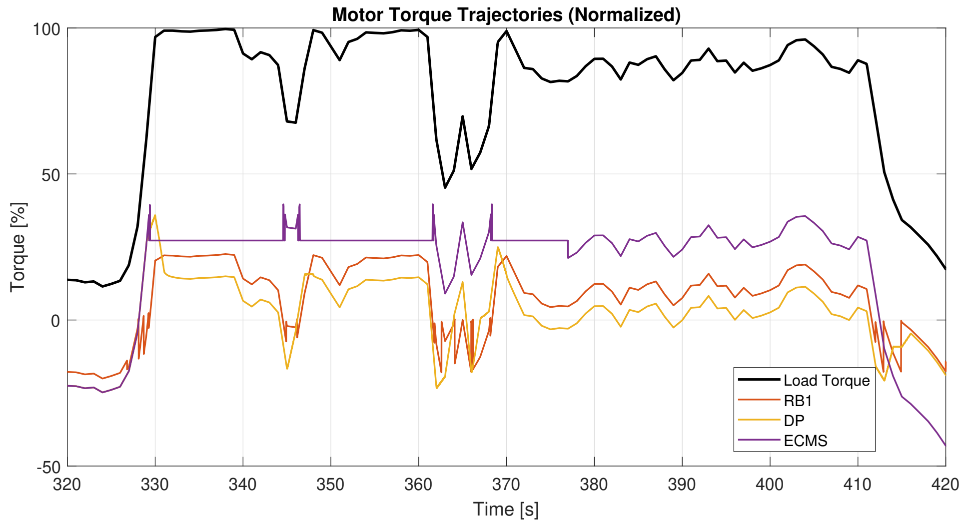

Figure A.2: Motor torque trajectories tracking comparison for all algorithms.

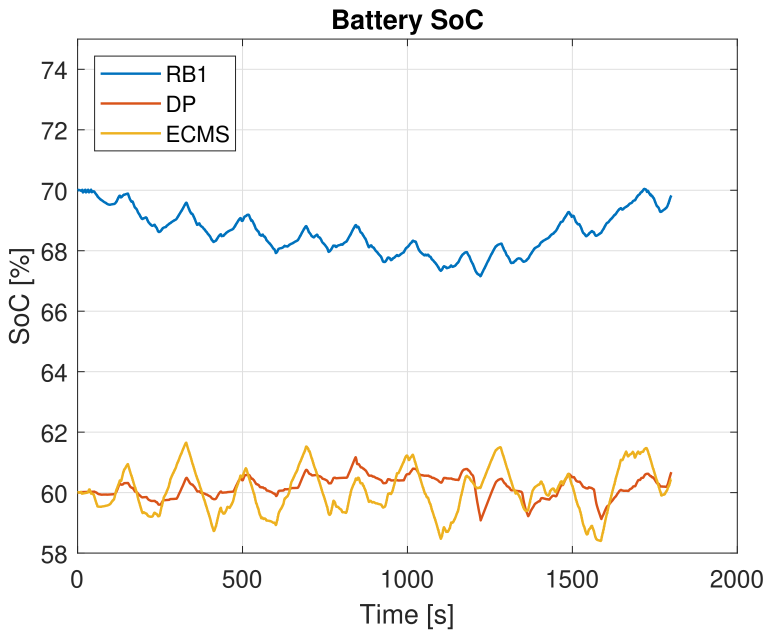

Figure A.3: Battery SoC trajectories comparison for all algorithms.

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