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A Holistic Approach Towards Energy Efficient Excavators

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Abstract

In the context of the need to reduce greenhouse gas emissions, the construction equipment industry is experiencing a transformative shift.

For decades, excavators have been designed to deliver high performance while maintaining cost-effectiveness. Hydraulic systems provide an easy way of energy distribution from the prime mover to the individual motion function. Robust components with high energy density have been a key factor. Energy efficiency has often been taken with lower priority.

By introduction of electric drives into general purpose machinery, energy consumption becomes a critical factor, especially in case of using batteries as a primary energy storage. At the same time new ways of energy distribution are provided.

A holistic approach will be demonstrated by utilizing architectural methods evaluating established and emerging technologies to identify innovative solutions that can optimize energy efficiency while considering economic viability.

Through a comprehensive analysis of technological advancements alongside their economic implications and commercial availability, this exercise will provide valuable insights for academia and industry stakeholders by driving the future of energy-efficient construction machinery.

Keywords: Energy efficiency, fuel consumption, carbon footprint, BEV, hydraulic systems

1. INTRODUCTION

This study focuses on motion system concepts for battery-electric medium-size excavators with an operating weight between 15 and 30 t. As a reference, a state-of-the-art diesel-driven 22 t crawler excavator is used. The goal is to identify, structure, and evaluate potential solutions for energy- and cost-efficient motion systems that are suitable for battery-electric operation.

Both academic concepts and industrial motion systems are considered. Using an architectural approach, all relevant system variants are mapped in a structured manner, enabling a systematic comparison in terms of energy efficiency, technical feasibility, and expected costs.

2. FUNDAMENTALS ON HYDRAULIC SYSTEMS FOR EXCAVATORS

A comprehensive review of hydraulic system concepts from academia and industry suitable for excavator applications reveals several fundamental system principles. Today's market is still dominated by throttle valve-controlled metering systems, while alternative concepts are emerging.

Valve metering systems remain highly attractive due to their excellent controllability at comparatively low cost. Power distribution is provided in a quite effective way. Energy efficiency is typically considered with lower priority.

In conventional internal combustion engine (ICE) driven machinery, this drawback has been tolerated because the energy density of fossil fuels is high, and fuel costs have been in an acceptable range.

With the rising of battery-electric construction machinery, the need for more energy-efficient motion systems is more urgent than ever. Batteries are costly and have limited energy density. Simply replacing the diesel engine with an electric motor without changing the hydraulic architecture results in limited operating time per charge due to the low overall efficiency of conventional motion systems. Just increasing the battery capacity is constrained both by cost and by the limited installation space in the machines.

At the same time, electric drives open new possibilities. Battery-electric machines can employ multiple electric motors on board, enabling advanced hydraulic and electro-hydraulic architectures that directly support more efficient motion systems.

When energy efficiency is prioritized, it becomes evident that inherent system losses must be minimized. Besides throttling losses at individual control functions, pressure compensation losses between functions play a significant role in hydraulic systems. Energy recuperation is rarely used in current excavator applications, even though a medium-size excavator typically comprises 5 to 10 main working functions, frequently operated simultaneously.

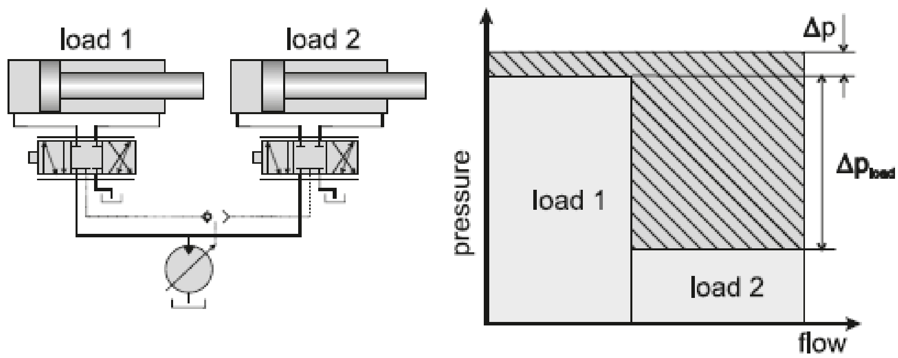


Figure 2.1. Typical single-circuit load-sensing hydraulic system [1]

Higher efficiency can be achieved by using multiple hydraulic circuits supplied by dedicated pumps or by employing more sophisticated architectures that systematically reduce throttling and compensation losses.

2.1. Paths Towards Throttle-Free Hydraulic Control

Two main technological paths towards throttle-free hydraulic control can be identified:

- the Common Pressure Rail (CPR) hydraulics path
- the Displacement Controlled Hydraulics (DCH) path,
  or rather known as Pump Controlled Hydraulics (PCH)

In Common Pressure Rail hydraulics, the system employs a plurality of nearly constant pressure rails, typically supported by hydraulic accumulators. This architecture inherently provides the possibility of energy recovery. A combination of discrete valves and hydraulic transformers is used to control the actuators. For linear actuation, multi-chamber cylinders can be applied to enable advanced flow and pressure management [1]. Hydraulic transformers can appear in both technological paths, but in this study, they are primarily allocated to the Common Pressure Rail approach.

In Displacement Controlled Hydraulics, a linear actuator is directly driven by the displacement of dedicated hydraulic pump unit. The actuator speed is controlled by the pump flow, without interfering throttle elements. Speed can be adjusted via pump rotational speed and/or variable displacement, while the motion direction is determined by the direction of the hydraulic flow.

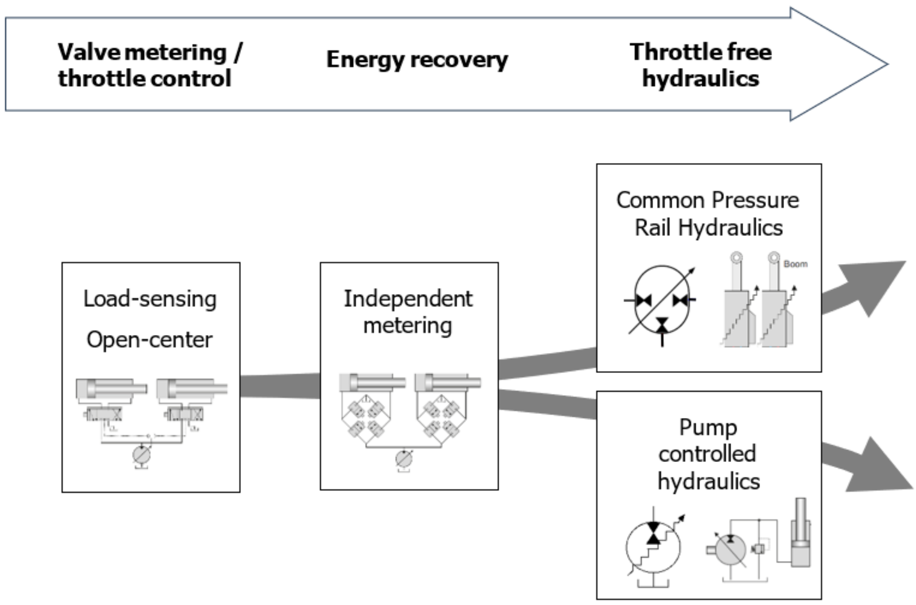


Figure 2.2. Possible paths towards throttle-free hydraulic control

The above-shown basic system principles can be combined in various ways or complemented by additional elements, resulting in hybrid architectures that further optimize efficiency, controllability and cost while the CPR and PCH principles are rather diverging.

3. ARCHITECTURAL APPROACH

The excavators' motion and control system can be clustered into its basic elements. Following the energy flow from the supply side via distribution & control towards the actuation of the working functions.

Those basic elements could be either commercially available components out of the shelf, parts under development or even theoretical ideas from academia.

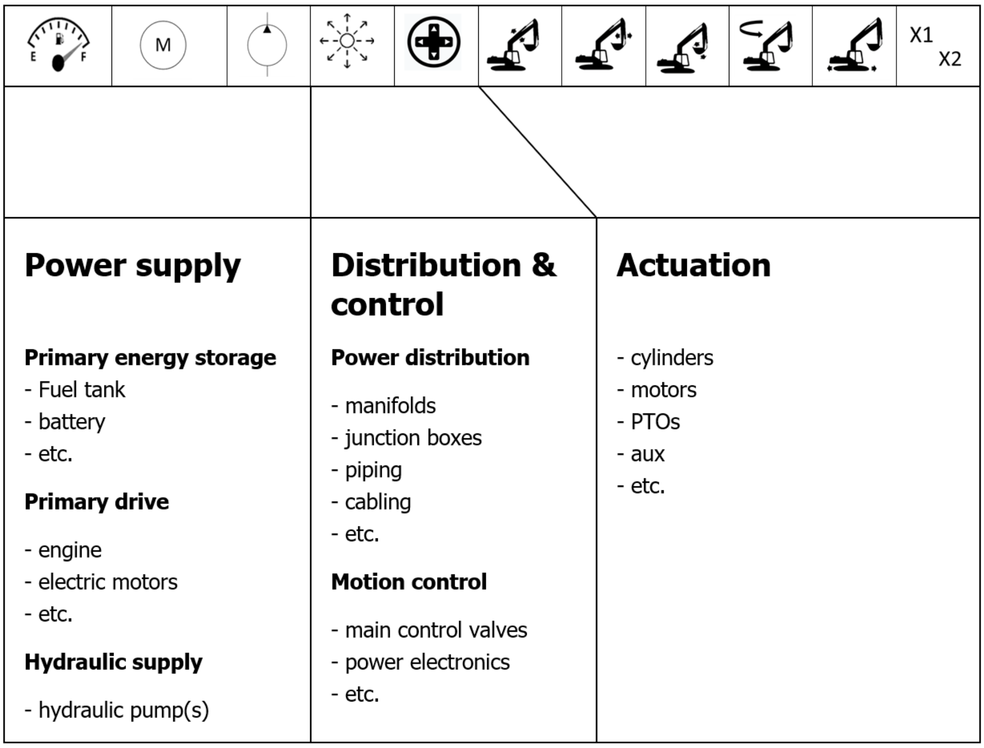


Figure 3.1. Architectural approach

3.1. Concept Creation

The excavator's motion and control system is decomposed into its basic architectural elements along the energy flow: from the energy supply (prime mover and energy storage), through the energy distribution and control subsystems, to the actuation of the individual working functions. These basic elements may be:

- commercially available off-the-shelf components,
- components under industrial development, or
- conceptual solutions proposed in academic research.

This architectural decomposition allows systematic generation and comparison of motion system concepts by combining compatible elements into complete system configurations.

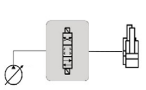
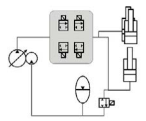
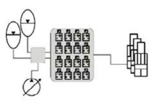
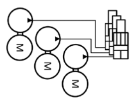
	Throttle Control	**IMVT**	**CPR**	**PCA**	**...**
					
Primary energy storage	**Tank A** xxx litre xxx €	**Tank A** xxx litre xxx €	**Tank B** xxx litre xxx €	**Battery A** xxx kWh xxxxx €	
Primary Drive	**Engine A** xxx kW xxxx €	**Engine A** xxx kW xxxx €	**Engine B** xxx kW xxxx €		
Hydraulic supply	**Pump A** xxx cc/rev xxxx €	**Pump C** xxx cc/rev xxxx €	**Pump C** xxx cc/rev xxxx €		
		Pump D xxx cc/rev xxxx €			
Power distribution	**Hose A** xxx bar xx €	**Hose A** xxx bar xx €	**Hose A** xxx bar xx €	**Cable A** xx mm² xx €	
		Hose B xxx bar xx €	**Manifold A** xx ports xx €	**Junction box A** xx ports xxx €	
Motion control	**MCV A** xx functions xxxx €	**MCV B** xx functions xxxx €	**MCV C** xx functions xxxx €	**Inverter A x3** xxx A xxxx €	
Actuation boom	**Cylinder A** d x D x l xxx €	**Cylinder A** d x D x l xxx €	**Cylinder B** d x D x l xxx €	**Motor A** xxx kW xxxx €	
				Pump E xxx cc/rev xxx €	
Actuation arm	**Cylinder C** d x D x l xxx €	**Cylinder C** d x D x l xxx €	**Cylinder D** d x D x l xxx €	**Motor A** xxx kW xxxx €	
				Pump E xxx cc/rev xxx €	
Actuation bucket	**Cylinder E** d x D x l xxx €	**Cylinder E** d x D x l xxx €	**Cylinder F** d x D x l xxx €	**Motor B** xxx kW xxxx €	
				Pump F xxx cc/rev xxx €	
Actuation swing	**Motor D** xxx cc/rev xxxx €	**Motor D** xxx cc/rev xxxx €	**Motor E** xxx cc/rev xxxx €	**Motor C** xxx kW xxxx €	
...					

Figure 3.2. Concept matrix

3.2. Concept Selection and Evaluation

By combining the different architectural sub-components, a broad variety of motion system concepts for medium-size excavators is generated. In parallel, a streamlined power and loss calculation methodology is developed to quantify the potential energy efficiency of each concept under representative duty cycles. The outcome is a comparative assessment of motion system cost versus input energy reduction for the entire excavator. This provides an overall picture of the trade-offs between efficiency, complexity, and economic viability.

Several of the investigated concepts are already commercially available in the construction equipment industry. Others have been analysed in more depth using simulation or experimentally validated on demonstrator machines. Battery-electric excavators in particular act as a strong driver for the adoption of more efficient motion systems, as they directly benefit from reduced energy demand via smaller batteries, lower charging requirements, and improved total cost of ownership.

3.3. Advanced Hydraulic Systems - Commercially Available

As a brief excursus a few examples on already commercially available advanced hydraulic motion systems:

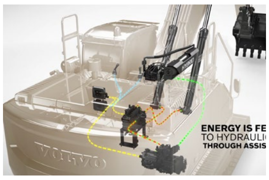
Single function IMVT	**Full-scale IMVT**	**CPR System**
		
Open-Center system combined with independent metering for boom-down energy recuperation.	Full scale independent metering valve technology	Common Pressure Rail system with Digital Valve Actuators and Secondary Controls.
Commercially available for medium and large excavators.	Commercially available for large excavators.	Commercially available for large excavators
+ limited complexity + cost efficient + robust and proven technology	+ significant energy efficiency improvement + limited impact on general machine layout	+ high energy efficiency improvement + supply system downsizing
- limited energy efficiency	- system complexity	- complex motion control - increased system costs

Figure 3.3. Commercially available products with advanced hydraulics

4. HYBRID SYSTEM APPROACH

As electric construction machinery is emerging, the range of possible motion and control systems is expanding. Inspired by industrial robotics, one might consider driving all functions with electric motors or electro-mechanical actuators (EMA). For rotary functions like swing of the upper carriage of an excavator or the traction drives, it comes rather naturally to directly apply those with electric propulsion.

Excavators digging attachment, however, must provide high forces and high speeds while being robust against mechanical shocks and dynamic overload in a rough terrain. Meeting all these requirements simultaneously with purely electro-mechanical actuators becomes challenging [3]. In addition, packaging constraints, component masses, and costs must be carefully considered.

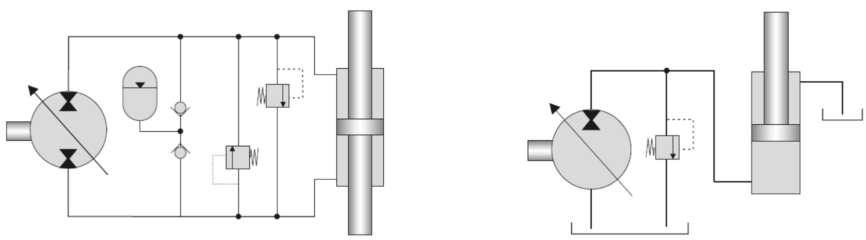
This raises also the question of energy efficiency: Will electro-mechanical solutions automatically outperform hydraulics?

In an EMA-based system, all propulsion and recuperation power flows through the electro-mechanical drive chain, and therefore experiences the associated losses:

- Bearing and mechanical transmission losses
- Electric motor losses
- Power electronics and conversion losses
- Energy storage system (ESS) losses

Considering an excavator working function with high recuperation potential, such as the boom, offers a useful benchmark. Up to 50 % of the required lifting capacity may be due to the dead weight of the structure and its attachment. This justifies a more complex and potentially more expensive motion system, as the benefits in terms of reduced primary energy storage demand and lower energy consumption (and thus total cost of ownership) can outweigh the additional system cost.

In contrast to EMA, Electro-Hydraulic Actuator (EHA) systems allow various different layout concepts that can be tailored to the specific use case [1][5].



(a) *Pump control in a closed circuit arrangement.*

(b) *Pump control in an open circuit arrangement.*

Figure 4.1. Two basic EHA system examples

For example, open- or closed-circuit layouts can be chosen (figure 4.1). Depending on the application, either plunger-, synchronous- or differential cylinders may be the favored choice. Whereas differential cylinders dominate in construction machinery. With the differential flow one of the challenges for EHA systems needs to be considered. Those cannot be simply driven by conventional pumps or pump-motors without further valve technology and storage devices. This will add cost and complexity on one hand, but also provides opportunities to increase the system's efficiency. If a pressurized reservoir in form of a hydraulic accumulator is built-in, this could offer the chance for short term energy buffering or counter-balancing a load.

For an excavator's boom dead weight compensation, a power-split concept (as illustrated schematically in Figure 4.2) can be highly advantageous in terms of energy efficiency. The static load component can be compensated in the hydraulic domain using hydraulic accumulators, while the electric drive primarily provides speed and directional control. Consequently, the power throughput in the electric subsystem is reduced, lowering conversion losses. A significant share of the energy flow remains within the hydraulic domain, and overall efficiency of the specific motion function of up to 80 % can be achieved.

Optimizing and partially decoupling a single motion function not only reduces the power consumption of that particular function. The remaining (hydraulic) motion system also benefits through reduced supply and compensation losses, thereby improving the efficiency of the entire machine significantly.

Considering the above-mentioned aspects, a hybrid system approach for an electric driven excavator could be drawn as shown in figure 4.2.

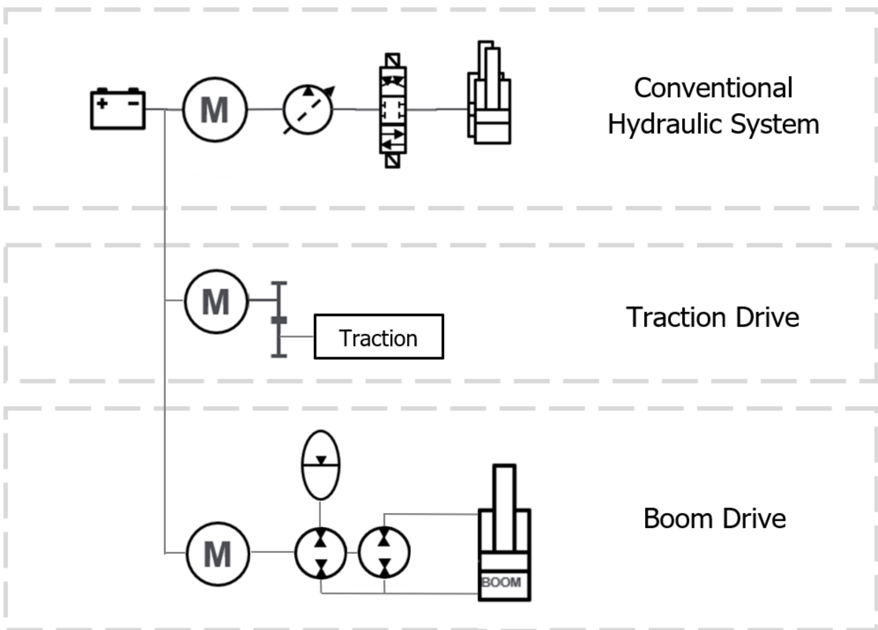


Figure 4.2. Hybrid motion system approach

A hybrid system, as illustrated above, emerged as a promising conceptual result of the architectural approach. The corresponding analysis indicates both a significant improvement in energy efficiency and a considerable economic potential.

The system was simulated and subsequently implemented in a demonstrator machine. As shown in figure 4.3, a substantial reduction of the total input power of approximately 27% was achieved in the dedicated load cycle, although other applications may show different figures. The energy portion of the boom function was reduced by about 10%, which lies within the expected range, while the energy efficiency of the remaining functions improved by approximately 17% in parallel. This can be explained since in conventional hydraulic systems, the boom drive constitutes the most dominant function and typically causes considerable compensation losses for the other functions used in parallel, such as arm, bucket, and swing. By decoupling the boom function, the compensation losses of the remaining functions are significantly reduced.

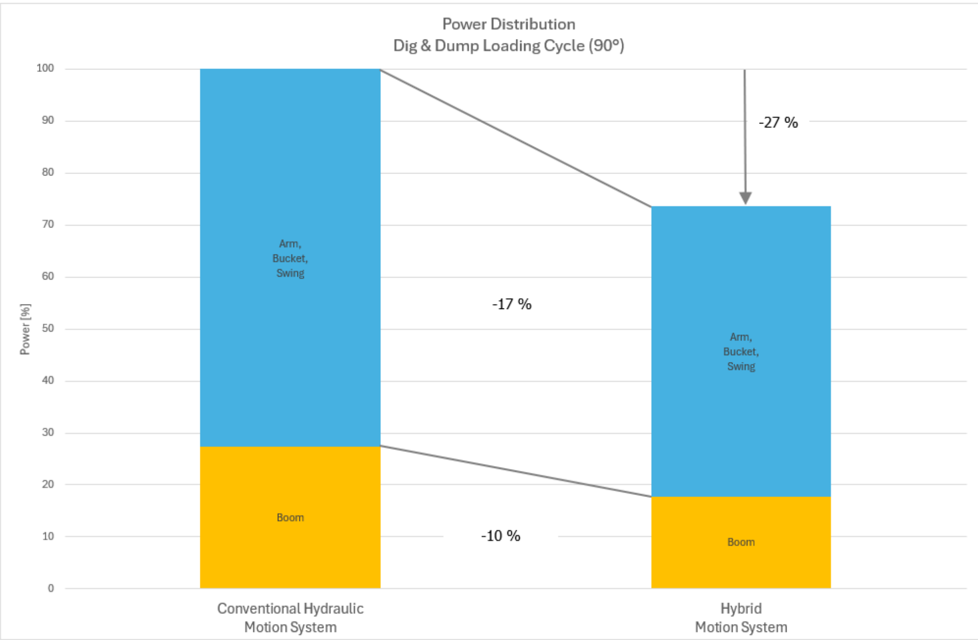


Figure 4.3. Comparison of the power distribution of a dig & dump loading cycle

5. Conclusion and Outlook

The study has been carried out by a cross-functional, international project team within Volvo Construction Equipment. The objective was to derive a motion system technology roadmap for construction machinery, with a focus on excavators and their transition towards electrification.

Technologies and concepts from both academia and industry were evaluated using an architectural approach. Several solutions have been implemented on demonstrator machines or selected as candidates for series development. The analysis confirms that there is no universal, one-fits-all solution that simultaneously delivers maximum performance at minimum cost. In the hydraulic domain in particular, a wide variety of technical solutions exist, suited to different applications and boundary conditions.

As one example a hydraulic hybrid system approach has been showcased in this study to demonstrate that it could be advantageous to optimize only one single machine function by a rather complex system. Nevertheless, there was a substantial benefit for the rest of the hydraulic system as compensation and supply losses are significantly reduced.

However, by systematically applying architectural methods and smartly combining appropriate elements, viable pathways towards significantly higher energy efficiency can be defined. These pathways support the development of economically attractive, energy efficient construction machinery and provide a structured foundation for future research and industrial implementation.

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Nomenclature

IMVT	Independent Metering Valve Technology
PCH	Pump Controlled Hydraulics
CPR	Common (or constant) Pressure Rail hydraulic system
DCH	Displacement Controlled Hydraulics
EMA	Electro-Mechanical Actuator
EHA	Electro-Hydrostatic Actuator
ICE	Internal Combustion Engine
ESS	Energy Storage System

Biographies

 

Heiko Steinbach received his diploma degree in Mechanical Engineering from Fachhochschule Trier in 2005, with focus in hydraulics as well as commercial vehicle and off-road applications.

He has more than 20 years of experience in the hydraulic domain, including several years in the automotive industry, where he focused on electro-hydraulic transmission controls.

Since 2011, he has held various roles in excavator development at Volvo Construction Equipment. He is currently working as System Owner for Motion Systems.

Kim Heybroek received his MSc degree in Mechanical Engineering from Linköping University, Sweden in 2006. In 2008, he joined Volvo Construction Equipment in Eskilstuna. In 2017, he received his PhD degree at the Department of Fluid Power and Mechatronic Systems at LiU. He is currently working as a network and research area leader in the field of hydraulics.