A general approach for the optimization of power distribution architectures of hydraulic Off-Road Vehicles

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***Abstract*— This paper presents a general optimization framework for hydraulic power distribution architectures of electrified off-road vehicles. Two complementary formulations are developed to evaluate independent metering (IM) valve configurations: a mixed-integer bilinear program for 3/3 valve architectures and a non-convex mixed-integer quadratically constrained program (MIQCP) for generic 2/2 valve topologies defined through a connectivity matrix. The framework explores key design variables including number of valve per actuator, secondary pressure line for flow regeneration, cross-port connections, and multi-pump arrangements. Validated on experimental digging cycle data from a Volvo ECR58 mini-excavator, results show that a 4-valve 2/2 IM architecture with a secondary pressure line achieves 53.6% energy savings over a conventional load sensing (LS)system. Adding a fifth cross-port valve yields 6.4% additional savings, while a fully connected topology reaches 16.6% further reduction at increased hardware complexity. These findings demonstrate that optimized independent metering with flow regeneration can substantially enhance the energy autonomy of electrified construction machinery.**

I. INTRODUCTION

To address growing environmental concerns, the European Union has tightened emission regulations such as the Stage V standards and the EU Emissions Trading System (EU ETS), compelling industries including the construction sector to significantly reduce CO_2 emissions and fuel consumption. Construction machinery, which traditionally relies on diesel engines for their high torque, energy density, and robustness, is directly impacted by these regulations.

Full electrification of construction equipment remains limited in practice. Electromechanical actuators (EMAs) are less suited than hydraulic or electrohydraulic actuators (EHAs) for heavy-duty applications, as rigid mechanical transmissions are more vulnerable to shock loads and transient forces. Consequently, hybrid architectures combining electric motors with hydraulic power transmission have emerged as a more viable path. However, conventional valve-controlled hydraulic systems suffer from inherently low efficiency—an investigation by Oak Ridge National Laboratory reported an average efficiency of only 21% for mobile hydraulic applications in the US market [1]. The main sources of these losses are throttling in directional control valves and the dissipation of recoverable energy during assistive load phases [2]. Combined with the limited energy density of batteries compared to diesel fuel, these inefficiencies severely reduce the operational autonomy of electrified machines.

To overcome these limitations, recent research has explored alternative hydraulic distribution architectures. Pump-controlled (or displacement-controlled) systems, where a variable-speed electric motor drives a fixed-displacement pump close to the actuator, have shown significant efficiency gains by eliminating throttling losses [1], [3]. Casoli *et al.* compared load sensing and electro-hydraulic solutions on a 9-ton excavator and demonstrated substantial energy savings with closed-circuit EHA configurations [3]. Similarly, Zhao *et al.* showed that motor-controlled cylinders can achieve 60–64% total energy savings over conventional valve-controlled systems [4]. In parallel, energy regeneration strategies—particularly boom potential energy recovery—have been extensively studied as a means to further improve the energy balance of hydraulic excavators [5], [6]. These developments highlight the critical role of hydraulic architecture optimization and energy recovery in enabling the electrification of construction machinery.

This paper addresses these challenges by designing the optimal power distribution architecture based on individual metering (IM)valves. The problem is addressed considering on one hand an offline optimization case, where all the possible degrees of freedom are explored in order to offer a computer aided design approach for any system complexity, and on the other hand a real-time optimization approach, based on linear programming based on the solution chosen from the first step. The remainder of this paper is organized as follows: Section II presents the context of this work, Section III describes the proposed framework for modeling the generic optimization problem, Section IV discusses the results obtained according to the considered architectures and Section IV concludes the paper by comparing these results with highlights on future prospects.

II. CONTEXT AND PROBLEM STATEMENT

Despite the advantages of hydraulic actuators in terms of power density, efficiency and robustness, conventional hydraulic systems still suffer from significant energy losses and nonlinearities caused by a power distribution based on valve throttling. Approximately 30% of energy losses are attributable to traditional directional control valves [7]. To address these inefficiencies, hydraulic individualization—the independent control of flow to each actuator—has emerged as a key design strategy. Two main approaches can be

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distinguished: displacement control (DC) and valve-based control with independent metering (IM).

A. Displacement-Controlled Systems

In displacement-controlled (DC) architectures, the actuator motion is regulated by varying the pump displacement or the motor speed, thereby eliminating throttling losses across directional valves. Multi-pump arrangements, where each actuator is driven by a dedicated pump (EHA), offer individual flow control and substantially higher efficiency.

A DC prototype mini-excavator developed at the Maha Fluid Power Research Center (Purdue University) demonstrated 40% fuel savings compared to a standard load sensing (LS) machine in side-by-side testing [8]. The evolution toward a series-parallel DC hybrid architecture (DC S-P) further improved efficiency, achieving a 50% reduction in engine power demand [9]. However, fully individualized DC systems (one pump and motor per actuator) are excessively more costly and exhibit slower dynamics compared to servo-hydraulic architectures, which may limit their applicability in high-bandwidth tasks.

B. Load Sensing and Independent Metering Systems

The simplest configuration uses a single pump supplying multiple actuators, which limits flexibility but minimizes cost. Load sensing (LS) is one of the most widely adopted approaches in this case in mobile hydraulics. The LS pump adjusts its displacement to deliver a flow rate that matches the demand of the highest-loaded actuator, while maintaining a constant pressure margin above the highest load pressure. Although LS systems are significantly more efficient than open-center circuits—achieving 45–55% hydraulic efficiency versus 25–35% [3]—they still suffer from throttling losses due to the mechanical coupling of traditional spool valves and the pressure margin imposed by the compensator. Combining LS with IM technology offers a promising path to further reduce these losses.

Independent metering (IM) consists in breaking the mechanical coupling between the meter-in and meter-out orifices of traditional spool valves, allowing each side of the actuator to be controlled separately. This decoupling provides additional control degrees of freedom, enables energy regeneration, and reduces throttling losses under low back-pressure conditions [7], [10]. Various terms exist for this concept, including separate metering, programmable valves, and multifunctional valves.

Although IM increases system flexibility and energy performance, it requires more components (typically four independent valves per actuator in a Wheatstone bridge configuration) and more complex control algorithms with mode switching logic [11]. The combination of IM with load sensing (LS) systems has been shown to yield significant energy savings while maintaining controllability. In [12], an IM system composed of two proportional 4/3 valves with a decoupled pressure-flow control strategy was tested on a three-degree-of-freedom manipulator, achieving a 45% reduction in energy consumption compared to a conventional LS system.

C. Holistic System Approaches

Rather than optimizing individual components, holistic approaches redesign the entire hydraulic architecture to maximize global efficiency. A representative example is the STEAM system (Steigerung der Energieeffizienz in der Arbeitshydraulik mobiler Arbeitsmaschinen), developed at RWTH Aachen University [13]. STEAM uses a constant-pressure system with two hydraulic accumulators (high and intermediate pressure) to decouple the actuators from the engine and pump. This architecture enables engine point operation at optimal efficiency, reduces throttling losses through multiple pressure rails, and allows energy recovery from all actuators. Experimental tests on a prototype excavator demonstrated 27% fuel savings over a standard LS system at the same cycle time [13]. However, controlling the transitions between pressure levels remains challenging and can lead to pressure oscillations.

D. Digital Hydraulic Systems

Digital hydraulics replaces continuously variable valves with arrays of fast-switching on/off valves, known as Digital Fluid Control Units (DFCUs). Each DFCU presents a set of parallel on/off valves whose combined response approximates proportional flow control. These valves are less sensitive to leakage and oil contamination than proportional valves [7]. The integration of digital hydraulics with IM has been identified as a major improvement for energy efficiency. However, digital hydraulic systems tend to be bulkier, more expensive, and may introduce noise and pressure spikes during valve switching. Despite these challenges, digital hydraulics has shown promising results in terms of energy savings and control performance in various applications, including mobile machinery [10].

E. Comparative Assessment

Electro-hydraulic actuator (EHA) systems—combining a variable-speed electric motor with a hydraulic pump in a closed or open circuit—have shown the most significant energy gains. In a study on a 9-ton excavator, EHA configurations achieved over 60% mechanical energy savings compared to a standard LS system, primarily by eliminating pressure compensators and directional valves [3]. IM-based systems offer a complementary approach by improving valve-controlled architectures with moderate hardware changes. Table I summarizes the key characteristics and reported energy savings of the main approaches.

Each approach offers a different trade-off between energy efficiency, system complexity, cost, and dynamic performance. EHA systems deliver the highest efficiency gains but require a dedicated electric motor and pump per actuator. IM systems provide substantial improvements at lower hardware cost by leveraging software-based control. Holistic systems such as STEAM achieve global optimization but introduce

TABLE I
COMPARISON OF HYDRAULIC DISTRIBUTION ARCHITECTURES

Architecture	Energy savings	Complexity	Cost
Load Sensing (LS)	Baseline	Low	Low
IM + LS	∼45%*	Medium	Medium
Displacement Control (DC)	∼40%	Medium	High
STEAM (holistic)	∼27%	High	Medium
EHA (pump-controlled)	>60%	Medium–High	High

*Savings vs. LS on a 3-DOF manipulator [12].

control challenges. These trade-offs must be carefully evaluated when selecting or designing a hydraulic architecture for electrified construction machinery.

The present work focuses on optimizing the design of IM-based distribution architectures for a mini-excavator, aiming to maximize energy savings while minimizing hardware complexity. The optimization framework considers various valve configurations, flow paths, and energy recovery options, and is validated using experimental data from a representative digging cycle.

III. METHODOLOGY AND AND PROBLEM FORMULATION

The reference system is a Volvo ECR58 mini-excavator (Fig.1) equipped with four main actuators: three linear cylinders (boom, arm, bucket) and one rotary motor (swing). Experimental data—including rod velocities, actuator forces, swing motor speed, flow rates, and pressure differentials—were recorded over a representative digging cycle. Previous studies [14], [15] evaluated independent metering (IM) configurations with 4 and 5 valves per actuator on this machine (Fig.2), achieving 36% and 37% energy savings respectively over the baseline load sensing (LS) system. Building on these results, the present work investigates additional IM-based distribution architectures and evaluates their energy performance through optimization.

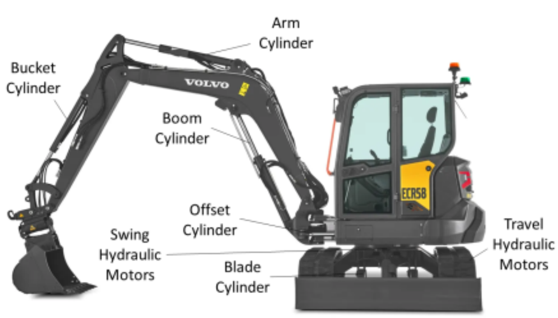

Fig. 1. Volvo ECR58 mini-excavator

The optimization of the IM architectures enables to control independently the pressures in each actuator chamber while

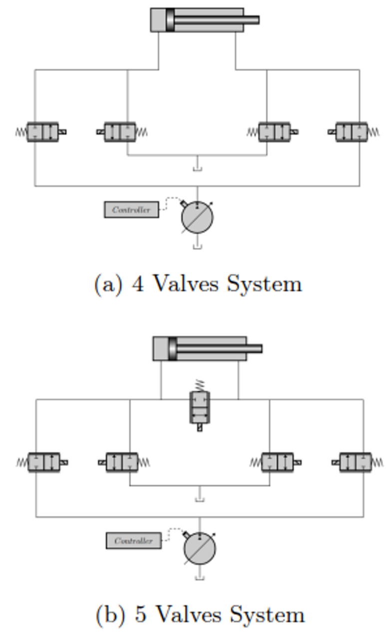

Fig. 2. Four or Five 2/2 valves configurations

satisfying the actuator flow and force requirements, and therefore minimize energy losses in valves, favour direct energy recovery from one cylinder to another or from one chamber of a cylinder toward the other one, and also reduce energy losses from braking.

The IM architectures considered in this study are based on a generic connectivity matrix (Fig.7) that defines the possible flow paths between the pump, tank, and actuator chambers. The main design variables include: (i) the number of valves per actuator (2/2 vs. 3/3), (ii) the presence of a secondary pressure line for flow regeneration, (iii) the inclusion of direct cross-port valves for inter-chamber flow, and (iv) the number of pumps and their displacement. The optimization framework evaluates the energy consumption of each configuration over the recorded digging cycle, accounting for realistic pump efficiency maps.

The main challenges in modeling and optimizing IM architectures include: (i) the nonlinear and non-convex nature of the valve flow equations, which involve square roots and absolute values; (ii) the bilinear cost function for pump power, which is the product of flow rate and pressure; (iii) the combinatorial complexity of mode switching logic for multiple actuators; and (iv) the integration of realistic pump efficiency maps into the optimization framework.

To address these challenges, two complementary optimization formulations are developed: a non-convex mixed-integer quadratically constrained program (MIQCP) that approximates the valve flow equations while enabling accurate solution to be calculated for offline analysis, and a mixed-integer bilinear program (MINLP) that enables reduced computation time in agreement with online optimization.

A. Governing Equations

The objective is to minimize the hydraulic pump power required to operate the system, expressed under steady-state conditions as:

$$P_W = Q_P \cdot (p_P - p_T) \tag{1}$$

where Q_P is the total pump flow rate, p_P the pump pressure, and p_T the tank pressure.

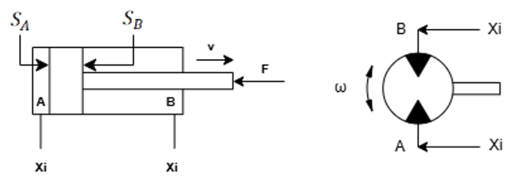

Fig. 3. Cylinder model / Motor model

For a linear actuator (Fig.3), the flow balance and force equilibrium are:

$$\sum Q_{X_i \to A} = S_A \cdot v, \quad \sum Q_{X_j \to B} = -S_B \cdot v \tag{2}$$

$$F = p_A \cdot S_A - p_B \cdot S_B \tag{3}$$

where S_A, S_B are the piston areas, v the rod velocity, and F the external load force, and X_i and X_j represent the inlet ports. For a rotary actuator (Fig.3), the analogous relations involve the displacement D_m and angular velocity ω:

$$\sum Q_{X_i \to A} = -\sum Q_{X_j \to B} = D_m \cdot \omega \tag{4}$$

$$T = (p_A - p_B) \cdot D_m \tag{5}$$

The flow through each valve is governed by the orifice equation:

$$Q_{X \to Y} = c_s \cdot S(u) \cdot \sqrt{\frac{2}{\rho}|p_X - p_Y|} \cdot \operatorname{sgn}(p_X - p_Y) \tag{6}$$

where c_s is the discharge coefficient, $S(u)$ the valve opening area, and ρ the fluid density. The square root and absolute value introduce nonlinearity and non-convexity in the optimization problem.

B. Optimization Formulations

Two optimization formulations are developed to handle the nonlinearities of (6) and the bilinear cost function (1).

1) Bilinear formulation: The first formulation models a distribution with two 3/3 valves per actuator (Fig.4), enabling both pump recovery and inter-chamber regeneration modes. Flow configurations are pre-compiled based on the sign of each actuator velocity, yielding 2^n possible configurations for n actuators. Binary variables d_i select between standard and recovery modes. The cost function $Q_P \cdot p_P$ is bilinear, and all other constraints are linear, resulting in a mixed-integer bilinear program [16].

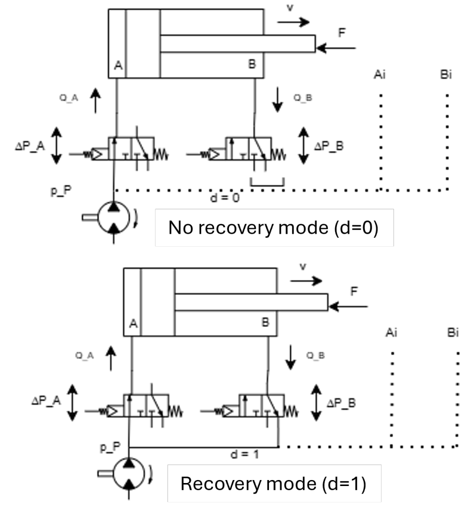

Fig. 4. Architecture based on 3/3 valves and used for Mixed-integer bilinear formulation

2) MIQCP formulation: The second formulation aims at exploring fully generic IM architectures with 2/2 valves (Fig.5 and 6). Moreover, these architectures include an additional valve between tank a secondary pressure line (H line) at pressure p_H. This enables flow regeneration between actuator chambers and enhances the direct flow recovery without requiring pump reversibility (motor mode).

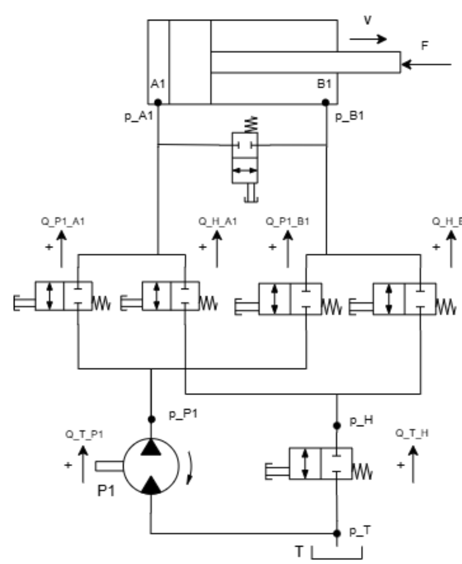

Fig. 5. Flow distribution for a single actuator based on five 2/2 valves with extended braking energy recovery (H line)

The second formulation uses a connectivity matrix (Fig.7) to model generically various IM architectures.

Squaring (6) removes the square root, yielding a quadratic constraint:

$$Q^2_{X_i \leftrightarrow Y_i} \leq K^2_{\max} \cdot |p_{X_i} - p_{Y_i}| \tag{7}$$

with the consistency condition

$$(p_{X_i} - p_{Y_i}) \cdot Q_{X_i \leftrightarrow Y_i} \geq 0 \tag{8}$$

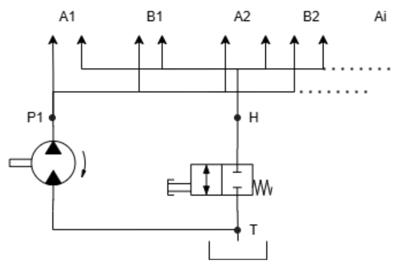

Fig. 6. Generic system architecture based on five 2/2 valves for each actuator with a common extended braking energy recovery line (H line)

The resulting problem is a non-convex Mixed-Integer Quadratically Constrained Program (MIQCP), which can be approximated by a MILP but at high computational cost [15].

	A1	B1	A2	B2	A3	B3	A4	B4	P1	H
A1		1							1	1
B1									1	1
A2				1					1	1
B2									1	1
A3						1			1	1
B3									1	1
A4								1	1	1
B4									1	1
P1										
H										

Pressures
p_A1
p_B1
p_A2
p_B2
p_A3
p_B3
p_A4
p_B4
p_P1
p_H

Flows
Q_P1_A1
Q_H_A1
Q_P1_B1
Q_H_B1
...
Q_P1_Ai
Q_H_Ai
Q_P1_Bi
Q_H_Bi

Fig. 7. Connectivity matrix for 4 actuators with 5 valves, a single pump, and an H line but without direct connection between cylinders

Four architectures (Fig.8) are evaluated using this formulation: (i) 4 valves/actuator with one pump, (ii) 5 valves/actuator (adding a direct cross-port regeneration path), and (iii) a fully connected configuration where all inter-chamber flow paths are allowed. Finally, a last configuration explore a multi-pump solution : (iv) 4 valves/actuator with two pumps (Fig.9).

The cost function minimizes both the pump supply power and the tank return power loss:

$$\min \sum_k Q_{P_k} \cdot p_{P_k} + \left(\sum Q_{H \leftrightarrow X_i}\right) \cdot (-p_H) \qquad (9)$$

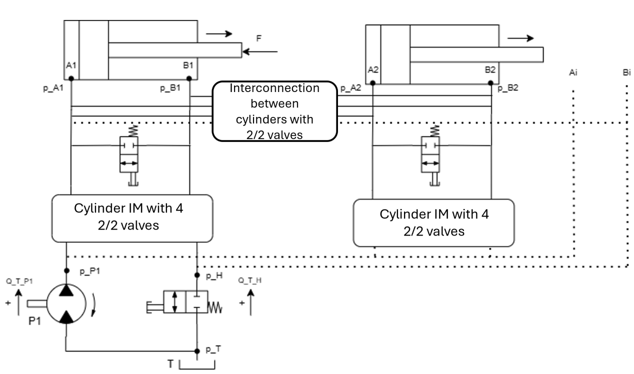

Fig. 8. Generic architecture

C. Pump Efficiency Integration

To account for real pump losses, the global pump efficiency $\eta_g(p_P, D)$—combining volumetric and hydro-mechanical efficiencies—is integrated into the cost function.

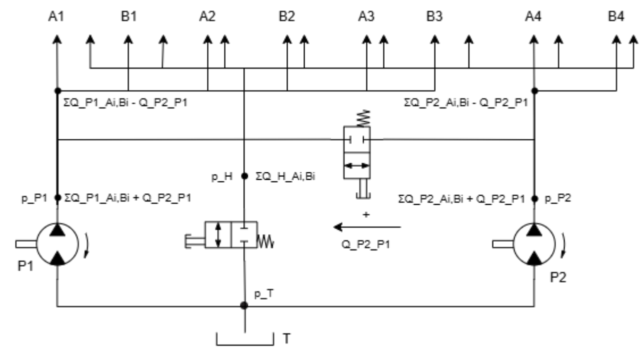

Fig. 9. Generic architecture with 2 pumps

Since the solver cannot handle products of more than two variables, the analysis of experimental efficiency maps reveals that the ratio $1/\eta_g$ can be approximated as a constant over the operating range (Fig.10). This is justified by the near-linear relationship between $p_P \cdot D/\eta_g$ and the pseudo-power $p_P \cdot D$. The cost functions are then simply scaled by the constant factor $1/\eta_g$, preserving the problem structure while capturing realistic pump losses, especially in multi-pump configurations.

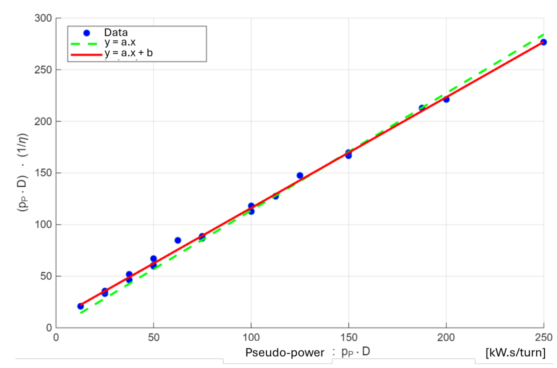

Fig. 10. Generic architecture

IV. Results and Discussion

The optimization problems are solved at each time step of the experimental digging cycle recorded on the Volvo ECR58 excavator. The total actuator useful energy over the cycle is 0.1574 kWh. All configurations are compared against the baseline load sensing (LS) system, which consumes 0.6469 kWh.

A. Comparison of Main Distribution Architectures

Fig. 11 shows the pump power profiles of the two main IM configurations alongside the total actuator power demand over the digging cycle. The 4-valve 2/2 system with a tank return restriction valve tracks the actuator demand most closely, indicating minimal throttling losses. Table II summarizes the energy consumption of all tested architectures.

The 4-valve 2/2 configuration with the intermediate pressure line p_H achieves the best performance, consuming 53.6% less energy than the LS system. This improvement

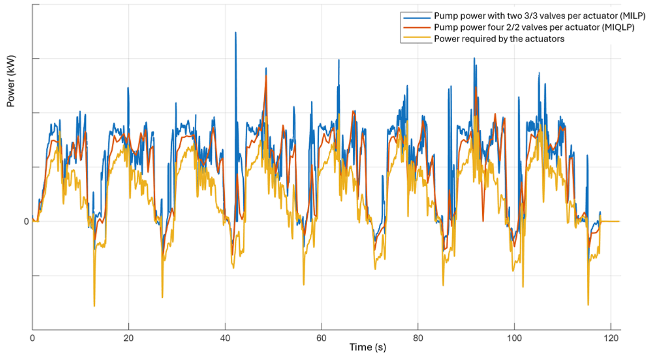

Fig. 11. Pump output power over the digging cycle for the 4-valve (2/2), 2-valve (3/3), and actuator power demand.

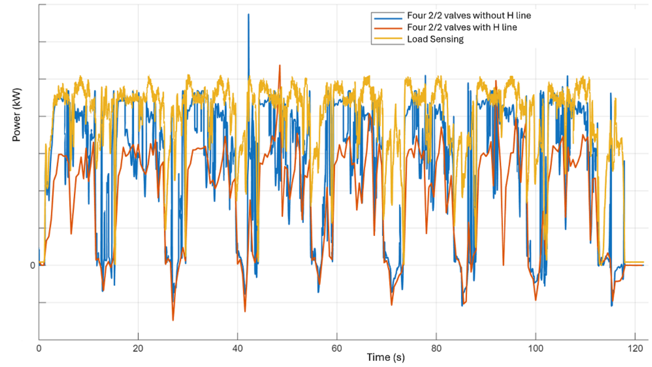

Fig. 12. Pump power comparison between LS, 4-valve 2/2 (without p_H), and 4-valve 2/2 (with p_H) over the digging cycle.

TABLE II
ENERGY COMPARISON OF THE MAIN DISTRIBUTION ARCHITECTURES

Architecture	Energy (kWh)	vs. LS
Load Sensing (LS)	0.647	—
4×2/2 valves (MINLP, no p_H)	0.437	−32.5%
2×3/3 valves (bilinear)	0.339	−47.6%
4×2/2 valves (MIQCP, with p_H)	0.300	**−53.6%**

TABLE V
ENERGY COMPARISON: SINGLE VS. DUAL PUMP (WITH PUMP EFFICIENCY)

Configuration	Energy (kWh)	vs. single pump
1 pump (90 L/min)	0.354	—
2 pumps (60 + 30 L/min)	0.347	−2.0%

is primarily due to the additional flow regeneration paths enabled by the secondary pressure line (H line), which redirects flow between actuator chambers instead of returning it to tank. As shown in Fig. 12, the LS system consistently exhibits higher pump power peaks than both 4-valve configurations, confirming the significant benefit of eliminating pressure compensators and enabling independent metering.

B. Influence of the Number of Valves

Table III compares the 4-valve, 5-valve, and fully connected configurations. Adding a direct cross-port regeneration valve (5-valve) yields a moderate 6.4% energy reduction, while connecting all possible inter-chamber flow paths results in 16.6% savings compared to the 4-valve baseline. However, the additional hardware cost and packaging constraints must be weighed against these incremental gains.

TABLE III
IMPACT OF INCREASING THE NUMBER OF VALVES PER ACTUATOR

Configuration	Energy (kWh)	vs. 4-valve	vs. useful
4×2/2 valves	0.300	—	+47.5%
5×2/2 valves	0.281	−6.4%	+44.0%
All paths open	0.250	−16.6%	+37.1%

TABLE IV
IMPACT OF VALVE DOWNSIZING ON ENERGY CONSUMPTION

Valve sizing	Energy (kWh)	vs. initial
Initial ($Q_{\text{nom}} = 104.6$ L/min)	0.30	—
Reduced ($Q_{\text{nom}} = 51.9$ L/min)	0.42	+28.6%

C. Effect of Valve Downsizing

An analysis of the normalized valve commands (Fig. 13) reveals that all commands remain below 0.5 in magnitude with the initial valve sizing, indicating significant oversizing. Reducing all valve nominal flow from 104 L/min to 51 L/min (at 70 bar) brings the commands within a ±0.7 range. However, as shown in Table IV, this downsizing increases energy consumption by 28.6% (0.30 → 0.42 kWh) due to higher throttling losses across the smaller orifices. Of course downsizing has to be studied for each valve independently. and a trade-off between valve cost/packaging and energy performance is necessary.

D. Influence of the Number of Pumps

Splitting the single 90 L/min pump into two smaller units (60 L/min + 30 L/min) yields only a 2% energy reduction when pump efficiencies are included (Table V). In principle, smaller pumps operating closer to their maximum displacement achieve better volumetric and hydro-mechanical efficiencies. However, the limited resolution of available efficiency maps and the use of nearly identical maps for both pumps restrict the validity of this analysis and requires a more detailed investigation with accurate pump models and experimental validation.

E. Pump-Motor Energy Recovery

Enabling the pump to operate in motor mode allows the recovery of 0.114 kWh over the cycle, reducing the total energy consumption from 0.312 kWh (pump-only) to 0.300 kWh—a 3.7% improvement. While the energy recovery is modest on this particular cycle, a pump-motor unit is more costly than a conventional pump. The economic viability of this option depends on the duty cycle characteristics and the frequency of assistive (overrunning) load phases.

V. CONCLUSION

This paper investigated the energy optimization of hydraulic distribution architectures for an electrified mini-

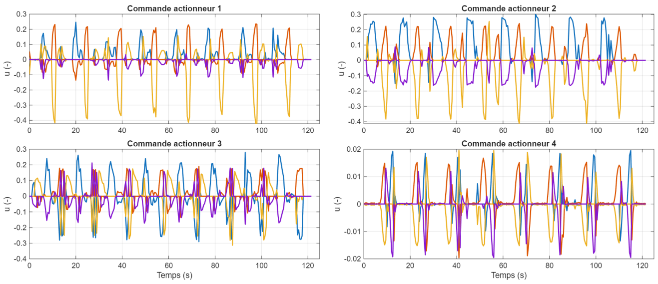

Fig. 13. Normalized valve commands for the 4-valve 2/2 configuration with initial valve sizing.

excavator through mathematical programming. Two optimization formulations—a mixed-integer bilinear program and a non-convex MIQCP—were developed to evaluate independent metering configurations under realistic operating conditions.

The main findings are as follows. First, a 4-valve 2/2 independent metering architecture with a secondary pressure rail achieves 53.6% energy savings compared to a conventional load sensing system, primarily through flow regeneration between actuator chambers. Second, adding a direct cross-port valve (5-valve configuration) yields a moderate 6.4% additional gain, while the fully connected architecture saves 16.6% more, suggesting diminishing returns relative to hardware complexity. Third, valve downsizing reduces cost and packaging but increases throttling losses ($+28.6\%$ energy), highlighting the need for careful sizing. Fourth, a dual-pump arrangement provides marginal improvement (-2%) under the tested conditions. Fifth, pump-motor energy recovery contributes 3.7% savings on the considered digging cycle.

These results demonstrate that independent metering with optimized flow distribution can substantially improve the energy autonomy of electrified construction machines. Future work will focus on extending the optimization to dynamic operating conditions, integrating more accurate pump efficiency models, and validating the approach experimentally on a prototype machine.

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