

SESSION A:

EARTH MOVING AND TRANSPORTATION MACHINERY

A fuzzy AHP approach for evaluating circular efficiency of hydraulic excavator swing drive systems

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ABSTRACT

Hydraulic excavators are among the most energy-intensive categories of heavy mobile machinery, characterized by intensive duty cycles, high energy demand, and significant environmental impact. Within the circular economy framework, the evaluation and design of key subsystems should not be limited to conventional performance indicators but should also include life-cycle-oriented criteria, such as durability, remanufacturing potential, resource efficiency, reliability, and user-related economic benefits. This paper proposes an integrated decision-making framework for assessing the circular efficiency of the hydraulic excavator swing drive system by combining engineering performance analysis with the fuzzy Analytic Hierarchy Process (fuzzy AHP). The application of triangular fuzzy numbers enables the modeling of uncertainty and subjectivity in expert judgments, thereby improving the robustness and reliability of criteria weighting. Based on a previously conducted energy-efficiency analysis of a 17-ton hydraulic excavator, two representative design alternatives were selected from a broader set of feasible configurations and evaluated according to hierarchically structured circular economy criteria. The results show that alternative L1 achieves higher overall circular efficiency than alternative L2, mainly due to better performance in energy efficiency, durability, and remanufacturing-related criteria. The proposed fuzzy AHP framework supports sustainable engineering design and component selection in heavy machinery systems.

KEYWORDS

Hydraulic excavator, Swing drive, Circular economy; Fuzzy AHP.

1. INTRODUCTION

In the current context of the European Union and the global industrial landscape, the heavy machinery sector is under increasing pressure to improve its energy and material efficiency in line with circular economy principles. The transition from linear to circular production models requires not only technological improvements, but also the development of decision-support frameworks capable of integrating technical, environmental, and economic aspects throughout the product life cycle. In this context, remanufacturing and improved drivetrain design represent important mechanisms for extending service life, reducing resource consumption, and lowering the total cost of ownership. According to studies by the Ellen MacArthur Foundation [1], machines with modular components, disassembly capability, and a high degree of reparability can achieve significantly lower emissions and resource consumption throughout their life cycle. Industrial companies such as Caterpillar and Engel confirm these findings through long-term remanufacturing programs, in which components are disassembled, restored, tested, and returned to service in “like-new” condition [2-4]. These practices demonstrate that engineering design decisions, especially at the subsystem and component level, have a direct influence on circular performance.

Hydraulic excavators are a representative category of heavy mobile machinery characterized by intensive duty cycles, high energy demand, and significant environmental impact. One of their key subsystems is the swing drive system, which enables the rotation of the upper platform during digging, material transfer, unloading, and return operations. The performance of this system depends on the interaction between the hydraulic motor, gearbox, axial bearing, and the operating conditions defined by load torque and platform rotational speed.

In the authors' previous research [4], a detailed energy analysis was conducted for the swing drive system of a 17-ton hydraulic excavator, consisting of a hydraulic motor 2.3 (Figure 1a), gearbox 2.4, and axial bearing 2.5.

The drive hydraulic motor is supplied, through the directional control valve 2.2, by the hydraulic pump 2.1, driven by the diesel engine 1 through the power divider 1.2 and the elastic coupling 1.1. The rotation of the platform is achieved by the rigid connection of the gearbox housing and the non-toothed ring of the axial bearing to the rotating platform L_2 (Figure 1b), while the gear z_{24} on the output shaft of the gearbox rotates in mesh with the stationary toothed ring of the axial bearing z_{25} , connected to the moving member of the excavator L_1 .

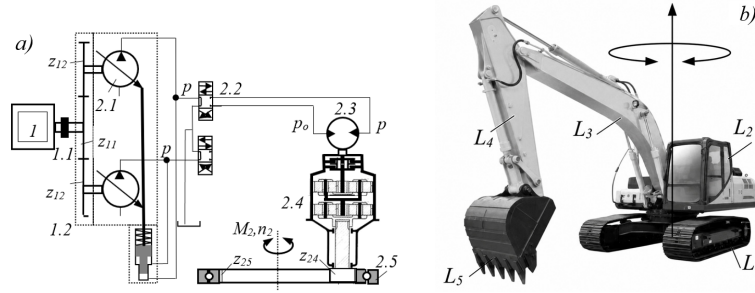


Figure 1: a) Swing drive of hydraulic excavator platforms with an open hydrostatic circuit
b) Hydraulic crawler excavator

The functional parameters of the drive mechanism of the excavator rotating platform are the output torque M_2 , equation (1), and the rotational speed n_2 of the platform, equation (2), determined by the equations [5]:

$$M_2 = \frac{(p - p_o) q_{mmax} \cdot \varepsilon_m \cdot \eta_{mm} \cdot i_r \cdot \eta_r \cdot i_l \cdot \eta_l}{2\pi} \quad (1)$$

$$n_2 = \frac{q_{pmax} \cdot \varepsilon_p \cdot n_p \cdot \eta_{pv} \cdot \eta_{mv} \cdot 1}{q_{mmax} \cdot \varepsilon_m \cdot i_r \cdot i_l} \quad (2)$$

where: q_{pmax} , q_{mmax} – the maximum specific flow of the hydraulic pump and the hydraulic motor, p , p_o – the pressure in the extension and retraction duct of the hydraulic motor, n_p – the number of the hydraulic pump revolutions, i_r , η_r – the transmission ratio and the degree of efficiency of the reducer, η_{pv} , η_{pm} , η_{mv} , η_{mm} – the volumetric and mechanical degree of efficiency of the hydraulic pump and the hydraulic motor, $\varepsilon_p = q_p/q_{pmax}$ – the hydraulic pump regulation range, $\varepsilon_m = q_m/q_{mmax}$ – the hydraulic motor regulation range, η_l – the degree of efficiency between the reducer and the axial bearing. Equations (1) and (2) show that, for the same desired functional parameters of the platform swing drive, different drive variants can be generated through the synthesis procedure by changing the pressure and flow rate of the hydraulic pump and by changing the size of the hydraulic motor and gearbox. Based on the specified functional parameters, imposed constraints, and formed databases of available drive component models, 94 possible variant solutions of the swing platform mechanism drive of the considered excavator model were generated using the developed program. From this set, two representative variants — VE10/1 and VE12/1 — were selected for further evaluation [5]. The analysis of the obtained results showed that the energy efficiency of the drive transmission variants differs considerably and changes with the functional parameters of the excavator platform rotation. In the zones of higher load torques and lower rotational speeds of the platform, corresponding to the transfer of the excavated material from the digging plane toward the unloading plane, variant VE10/1, with a hydraulic motor of lower specific flow and a gearbox of higher transmission ratio, achieves higher efficiency values. In contrast, variant VE12/1, with a hydraulic motor of higher specific flow and a reducer of lower transmission ratio, achieves higher efficiency values at lower load torques and higher rotational speeds of the platform, corresponding to the return from the unloading plane to a new digging plane, particularly at larger swing angles when higher platform rotational speeds can be achieved (Figure 2).

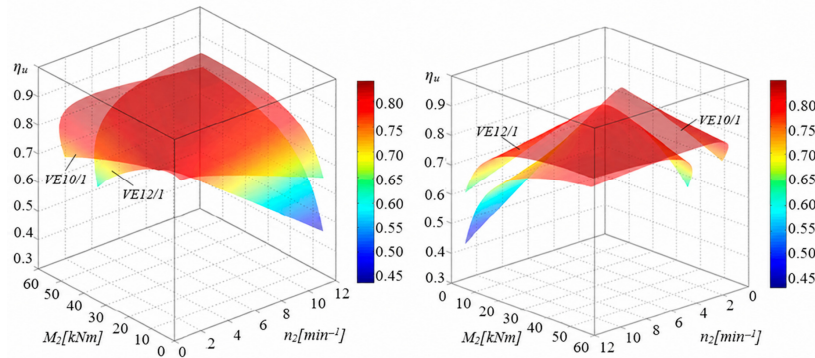


Figure 2: Efficiencies of the transmission: Both drive variants VE10/1 and VE12/1 [5]

Nevertheless, energy efficiency represents only one dimension of circular performance. A comprehensive assessment of swing drive systems must also include criteria such as durability, modularity, ease of disassembly, material quality, reparability, remanufacturing potential, resource efficiency, reliability, and user-oriented economic benefits. Many of these

criteria are inherently qualitative or uncertain, especially those related to reparability, environmental impact, and user perception, which makes their integration into conventional decision-making models difficult.

Despite the growing application of multi-criteria decision-making methods in engineering design, most existing studies rely on classical approaches, such as the Analytic Hierarchy Process (AHP), which assume precise and deterministic expert judgments. This represents a methodological limitation when dealing with complex engineering systems characterized by uncertainty and subjective evaluations, as is the case in circular economy-based assessments. To address this limitation, this paper proposes an enhanced decision-making framework based on the fuzzy Analytic Hierarchy Process (fuzzy AHP), where pairwise comparisons are expressed using triangular fuzzy numbers in order to better capture the vagueness and ambiguity of expert judgments.

Accordingly, the aim of this paper is to develop a comprehensive framework for evaluating the circular efficiency of hydraulic excavator swing drive systems by combining engineering analysis with fuzzy AHP-based multi-criteria decision-making. The proposed criteria set encompasses energy efficiency, durability and remanufacturing potential, environmental impact, resource efficiency, reliability, dynamic stability, and user-related economic benefits. Such a framework enables a more accurate and robust assessment of technical solutions and contributes to the rational design and selection of components aligned with circular economy principles in heavy machinery systems.

2. IDENTIFICATION OF CRITERIA BASED ON CIRCULAR ECONOMY PRINCIPLES

The process of defining criteria for the optimal selection of the hydraulic excavator swing drive system is based on the integration of technical, environmental, and economic aspects, in accordance with contemporary circular economy principles. The starting point in this process is the analysis of existing technical models of the swing drive system, including parameters such as energy efficiency, mechanical loads, dynamic stability, and losses in hydraulic and mechanical transmission. While these elements form the foundation of traditional engineering approaches, they must be extended by incorporating life-cycle-oriented criteria that reflect circular economy requirements. According to the European Commission's circular economy framework and the conceptual model of the Ellen MacArthur Foundation, industrial systems should be designed to enable life extension, remanufacturing, reparability, and reduced resource consumption throughout the entire life cycle. These principles are particularly relevant for heavy machinery systems, where components such as swing drives exhibit high material and energy intensity, but also significant potential for restoration through remanufacturing processes. The hierarchical structure of the decision model is defined across three levels. The first level represents the overall objective, which is the selection of a swing drive solution that maximizes circular efficiency by achieving an optimal balance between technical performance, durability, resource utilization, and environmental impact. The second level consists of seven primary criteria: energy efficiency, dynamic stability and mechanical loads, durability and remanufacturing potential, environmental impact, resource efficiency, reliability, and economic benefit to the user. The third level includes a set of subcriteria that enable a more detailed and structured evaluation of each criterion, thereby supporting consistent expert judgment within the fuzzy AHP framework. Energy efficiency represents one of the dominant evaluation domains and includes subcriteria such as hydraulic motor efficiency, transmission efficiency, losses in the gearbox, and total energy consumption per operating cycle. Given the high-frequency operation of the swing drive system, these parameters directly influence both environmental impact and operational costs over the machine's life cycle. Dynamic stability and mechanical loads constitute the second group of criteria and include parameters such as shock torques, angular accelerations, vibration levels, and thermal behavior. These factors are critical for assessing structural integrity and material fatigue, and from a circular economy perspective, they indirectly contribute to extending the service life of key components and reducing replacement frequency. Durability and remanufacturing potential form the third category and represent a central pillar of circular efficiency. Subcriteria include fatigue resistance, modularity of design, ease of disassembly, and compatibility with remanufacturing processes. Systems designed with these characteristics enable component recovery and reuse, resulting in substantial environmental and economic benefits. The environmental impact category includes parameters such as CO₂ emissions associated with manufacturing, hydraulic fluid consumption, and overall ecological footprint. These subcriteria enable the quantification of environmental performance and support the identification of solutions with reduced life-cycle impact. Resource efficiency focuses on system mass, material selection, and the use of critical raw materials. Solutions that employ recyclable materials or require less intensive processing during remanufacturing contribute to improved circular performance and reduced material footprint. Reliability and economic benefit to the user represent the final evaluation domains. Reliability is reflected through system stability, failure rates, and maintenance intervals, while economic criteria include maintenance costs, residual value, and availability of remanufacturing infrastructure. In addition, system availability is considered as a supporting indicator that directly links technical performance with operational efficiency, reflecting downtime duration and recovery capability. From a methodological perspective, it is important to emphasize that several of the defined criteria—particularly those related to remanufacturing potential, environmental impact, and user perception—are inherently uncertain and difficult to quantify precisely. For this reason, the application of the fuzzy AHP approach enables the incorporation of vagueness and subjectivity in expert evaluations by representing pairwise comparisons through triangular fuzzy numbers. This allows for a more realistic and robust modeling of decision-making conditions compared to classical deterministic approaches. Consequently, the defined criteria system provides a comprehensive and structured basis for evaluating the circular efficiency of swing drive systems, while the integration of fuzzy AHP ensures that the inherent uncertainty of engineering judgments is adequately addressed, thereby enhancing the reliability and applicability of the proposed decision-making framework.

3. FUZZY AHP EVALUATION OF CRITERIA AND ASSIGNMENT OF WEIGHT COEFFICIENTS

In order to enable a more realistic and robust comparison of criteria characterized by uncertainty and subjectivity, the classical Analytic Hierarchy Process (AHP) is extended through the application of the fuzzy AHP approach [7]. Unlike the conventional AHP method, which assumes precise numerical judgments, fuzzy AHP incorporates vagueness in expert evaluations by representing pairwise comparisons using triangular fuzzy numbers (TFNs). This allows for a more accurate modeling of decision-making conditions, particularly in the context of circular economy-based assessments, where several criteria are inherently qualitative and imprecise.

The linguistic importance of criteria is expressed using a fuzzy extension of the Saaty scale [6]. Each judgment is represented by a triangular fuzzy number:

$$\tilde{a}_{ij} = (l_{ij}, m_{ij}, u_{ij}) \quad (3)$$

where l_{ij} , m_{ij} , and u_{ij} denote the lower, modal, and upper bounds of the expert preference, respectively. The reciprocal condition is defined as:

$$\tilde{a}_{ij} = \left(\frac{1}{u_{ji}}, \frac{1}{m_{ji}}, \frac{1}{l_{ji}} \right), i \neq j \quad (4)$$

The fuzzy pairwise comparison matrix is then constructed as:

$$\tilde{A} = [\tilde{a}_{ij}]_{n \times n} \quad (5)$$

where n is the number of criteria.

To derive the weights of criteria, the geometric mean method proposed by Buckley is applied. For each criterion, the fuzzy geometric mean is calculated as:

$$g_i = \left(\prod_{j=1}^n a_{ij} \right)^{1/n} \quad (6)$$

The fuzzy weight vector is then obtained by normalization:

$$\tilde{w}_i = \tilde{g}_i \otimes (\sum_{i=1}^n \tilde{g}_i)^{-1} \quad (7)$$

where $\otimes$ denotes fuzzy multiplication.

In order to obtain crisp values suitable for further analysis, the fuzzy weights are defuzzified using the centroid method:

$$\tilde{w}_i = \frac{(l_i + m_i + u_i)}{3} \quad (8)$$

For each criterion, a fuzzy pairwise comparison matrix of alternatives is constructed following the same procedure. Local priorities of alternatives are calculated using the fuzzy geometric mean method and subsequently defuzzified to obtain crisp values. This ensures methodological consistency across all levels of the hierarchy.

The overall priority of each alternative is determined by aggregating local priorities with the corresponding criteria weights:

$$P_k = \sum_{i=1}^n w_i^* \cdot p_{ik} \quad (9)$$

where p_{ik} represents the local priority of alternative k with respect to criterion i .

3.1. Results and Interpretation

The application of the fuzzy AHP procedure was carried out in several consecutive steps in order to obtain criteria weights and the final ranking of the selected swing drive alternatives. First, the linguistic judgments used for pairwise comparison were transformed into triangular fuzzy numbers according to the fuzzy Saaty scale (Table 1.). This scale enables expert preferences to be expressed not as fixed crisp values, but as intervals that include the lower, modal, and upper values of judgment. In this way, uncertainty and subjectivity in expert assessments are incorporated directly into the evaluation process.

Table 1: Fuzzy Saaty scale (linguistic judgments and tfns)

Linguistic scale	Crisp value	Triangular fuzzy number (TFN)
Equal importance	1	(1, 1, 1)
Weak importance	2	(1, 2, 3)
Moderate importance	3	(2, 3, 4)
Moderate plus	4	(3, 4, 5)

Strong importance	5	(4, 5, 6)
Strong plus	6	(5, 6, 7)
Very strong importance	7	(6, 7, 8)
Very very strong	8	(7, 8, 9)
Extreme importance	9	(8, 9, 10)

Based on the defined linguistic scale, the original crisp pairwise comparison matrix was transformed into a fuzzy comparison matrix (Table 2.). The matrix includes seven primary criteria: energy efficiency, dynamic stability, durability and remanufacturing potential, environmental impact, resource efficiency, reliability, and economic aspect. The transformation into triangular fuzzy numbers preserves the initial expert judgments, while at the same time allowing the uncertainty of these judgments to be considered in the calculation of criteria weights.

Table 2: Fuzzy pairwise comparison matrix of criteria

Criteria a_{ij}	energy efficiency a_1	dynamic stability a_2	durability/ remanufacturing a_3	environmental impact a_4	resource efficiency a_5	reliability a_6	economic aspect a_7
energy efficiency a_1	(1,1,1)	(2,3,4)	(1,1,1)	(4,5,6)	(4,5,6)	(2,3,4)	(4,5,6)
dynamic stability a_2	(1/4,1/3,1/2)	(1,1,1)	(1/4,1/3,1/2)	(2,3,4)	(2,3,4)	(1,1,1)	(2,3,4)
durability/ remanufacturing a_3	(1,1,1)	(2,3,4)	(1,1,1)	(4,5,6)	(4,5,6)	(2,3,4)	(4,5,6)
environmental impact a_4	(1/6,1/5,1/4)	(1/4,1/3,1/2)	(1/6,1/5,1/4)	(1,1,1)	(1,1,1)	(1/4,1/3,1/2)	(1,1,1)
resource efficiency a_5	(1/6,1/5,1/4)	(1/4,1/3,1/2)	(1/6,1/5,1/4)	(1,1,1)	(1,1,1)	(1/4,1/3,1/2)	(1,1,1)
reliability a_6	(1/4,1/3,1/2)	(1,1,1)	(1/4,1/3,1/2)	(2,3,4)	(2,3,4)	(1,1,1)	(2,3,4)
economic aspect a_7	(1/6,1/5,1/4)	(1/4,1/3,1/2)	(1/6,1/5,1/4)	(1,1,1)	(1,1,1)	(1/4,1/3,1/2)	(1,1,1)

After forming the fuzzy pairwise comparison matrix, the fuzzy weights of the criteria were calculated (Table 3.) and then defuzzified to obtain crisp values suitable for further ranking of alternatives. The obtained results show that the highest weights are assigned to energy efficiency and durability/remanufacturing, each with a defuzzified value of 0.2939. These two criteria together account for almost 58.8% of the total importance, which confirms their dominant role in the evaluation of circular efficiency. This is expected, since energy efficiency directly affects operating costs and environmental impact, while durability and remanufacturing potential directly influence service life extension, component reuse, and circular value preservation. Dynamic stability and reliability follow with equal defuzzified weights of 0.1296. Their moderate importance indicates that mechanical behavior, operational stability, failure rates, and maintenance intervals are also relevant for circular performance, although they have a lower influence than energy efficiency and durability. Environmental impact, resource efficiency, and economic aspect have lower, but still relevant, weights of 0.0510 each. These criteria support the broader life-cycle interpretation of the system, especially in terms of material footprint, ecological effects, and user-related economic benefits. The local priorities of the alternatives were then determined for each criterion and aggregated with the corresponding criteria weights (Table 4.). The results show that alternative L1 achieves a higher overall priority than alternative L2. The overall priority of L1 is 0.6889, while the overall priority of L2 is 0.3111. This ranking is primarily influenced by the better performance of L1 in the most important criteria, especially energy efficiency and durability/remanufacturing. In addition, L1 also shows better local priorities in dynamic stability, environmental impact, reliability, and economic aspect, while both alternatives have equal priority with respect to resource efficiency.

Table 3: Fuzzy weights and defuzzified values

Criteria	Fuzzy weight (l, m, u)	Defuzzified weight
Energy efficiency (a1)	(0.2001, 0.2972, 0.4306)	0.2939
Dynamic stability (a2)	(0.0821, 0.1274, 0.1998)	0.1296
Durability/reman. (a3)	(0.2001, 0.2972, 0.4306)	0.2939
Environmental impact (a4)	(0.0366, 0.0502, 0.0742)	0.0510
Resource efficiency (a5)	(0.0366, 0.0502, 0.0742)	0.0510
Reliability (a6)	(0.0821, 0.1274, 0.1998)	0.1296
Economic aspect (a7)	(0.0366, 0.0502, 0.0742)	0.0510

Table 4: Local Priorities and Overall Ranking of Alternatives

Criteria	L1	L2
Energy efficiency	0.75	0.25
Dynamic stability	0.67	0.33
Durability/remanufacturing	0.67	0.33
Environmental impact	0.67	0.33
Resource efficiency	0.50	0.50
Reliability	0.67	0.33
Economic aspect	0.75	0.25
Overall priority	0.6889	0.3111

The obtained ranking indicates that alternative L1 provides a more favorable balance between engineering performance and circular economy requirements. Its advantage is mainly associated with criteria that have the greatest influence on the final decision, namely energy efficiency and durability/remanufacturing potential. At the same time, the difference between the alternatives should not be interpreted as absolute or extreme, since the two variants are structurally and functionally similar and belong to the same group of feasible swing drive solutions.

The fuzzy AHP results also show that the obtained criteria weights are highly consistent with the classical AHP results, while the ranking of alternatives remains unchanged. This confirms the robustness and reliability of the proposed decision-making framework. The main advantage of the fuzzy AHP approach is that it captures uncertainty in expert judgments and avoids overly rigid preference assignments typical of classical AHP. As a result, the final ranking is both mathematically consistent and better aligned with real engineering decision-making conditions, where criteria are often partly qualitative, uncertain, and dependent on expert interpretation.

4. DISCUSSION AND BROADER IMPLICATIONS OF THE FRAMEWORK (FUZZY AHP)

The results obtained using the fuzzy AHP approach provide more than a simple numerical ranking of the considered drive alternatives; they offer insight into the key technical attributes that contribute to the circular value of the system under conditions of uncertainty. The high importance assigned to energy efficiency and durability with remanufacturing potential confirms that the primary drivers of circular performance in heavy machinery are directly embedded in the design of the drive system. In particular, the selection of hydraulic motor displacement, gearbox configuration, and structural modularity has a decisive influence not only on operational performance, but also on service life extension, remanufacturing feasibility, and overall life-cycle costs. The application of fuzzy AHP enables a more realistic interpretation of these results by accounting for the inherent vagueness and subjectivity in expert evaluations. Criteria such as remanufacturing potential, environmental impact and user-related benefits cannot be precisely quantified in early design stages; therefore, the use of triangular fuzzy numbers allows these aspects to be incorporated into the decision-making process in a structured and analytically consistent manner. This enhances the reliability of the obtained priorities and strengthens the link between engineering judgment and decision outcomes. From a broader perspective, the proposed framework represents a practical bridge between engineering design and circular economy principles. The selected criteria-reparability, modularity, availability, and resource efficiency-are fully aligned with European policy objectives aimed at extending product life cycles and supporting remanufacturing markets (European Commission, 2015). Through the application of fuzzy AHP, these policy concepts are translated into measurable decision variables, enabling their direct integration into engineering design processes. Industrial practices further support these findings. Remanufacturing programs implemented by companies such as Caterpillar and Engel demonstrate that design decisions made at the component level have long-term implications for resource consumption, energy efficiency, and operational performance. Systems designed with higher modularity and reparability enable more efficient refurbishment processes, reduce material usage, and improve equipment availability, thereby contributing to both economic and environmental sustainability (Caterpillar Inc., 2020; ENGEL, 2020). From the perspective of end users, the obtained results have immediate practical relevance. The alternative identified as optimal (L1) achieves superior performance in the criteria most closely related to user value, including service life, system availability, and remanufacturing capability. This indicates that the selection of an appropriate drive configuration directly affects total cost of ownership, maintenance planning, and operational reliability. Consequently, the proposed framework supports decision-making not only at the design stage, but also in the context of equipment procurement and lifecycle management. In addition, the use of fuzzy AHP provides an important methodological contribution by ensuring that decision outcomes remain stable despite the presence of uncertainty in input judgments. This is particularly relevant for complex engineering systems, where precise data are often unavailable or incomplete. By capturing uncertainty within the evaluation process, the framework increases confidence in the obtained ranking and supports more robust and defensible engineering decisions. Therefore, the proposed fuzzy AHP-based framework can be applied not only as a tool for the selection of swing drive systems, but also as a broader decision-support methodology for designers, manufacturers, and policy makers. It enables the systematic incorporation of circular economy principles into technical decision-making and provides a foundation for the development of sustainable design guidelines, eco-design standards, and procurement strategies in the heavy machinery sector.

5. CONCLUSIONS

The proposed methodology has certain limitations that should be taken into account. Although the fuzzy AHP approach enables the incorporation of uncertainty and subjectivity in expert judgments, the evaluation process still depends on the quality and consistency of expert input, which may vary depending on the industrial context and type of machinery. In addition, the assessment of specific circularity-related criteria, such as environmental impact and remanufacturing potential, is influenced by the availability and reliability of practical data, which may differ across manufacturers and operational environments. In this paper, an integrated methodological framework was developed for assessing the circular efficiency of the swing drive system of a hydraulic excavator by combining engineering analysis with fuzzy AHP-based multi-criteria decision-making. Based on a previously conducted energy analysis, a comprehensive set of criteria was defined in accordance with circular economy principles, encompassing technical, environmental, resource, and economic aspects over the entire life cycle of the system. The results of the fuzzy AHP analysis indicate that alternative L1 achieves higher overall circular efficiency compared to alternative L2, primarily due to its superior performance in the most influential criteria, namely energy efficiency and durability with remanufacturing potential. These findings confirm that key design parameters, such as hydraulic motor displacement and gearbox configuration, play a crucial role not only in improving operational efficiency but also in extending component lifespan and enhancing circular performance. At the same time, the results show that the differences between the analyzed alternatives are not extreme, reflecting their structural and functional similarity. The application of fuzzy AHP ensures that such differences are evaluated in a balanced and realistic manner, avoiding overemphasis on individual criteria and enabling a stable and consistent ranking under conditions of uncertainty. The proposed framework represents a practical and robust tool for supporting decision-making in the design and selection of heavy machinery components. By integrating circular economy principles into a structured evaluation model, it enables the translation of abstract sustainability concepts into concrete engineering criteria. Furthermore, the alignment of the most influential criteria with European circular economy priorities highlights the relevance of the framework for supporting eco-design strategies and sustainable procurement policies. From the perspective of end users, the advantage of the selected alternative (L1) indicates the potential for reduced total cost of ownership, increased system availability, and more reliable maintenance planning. These findings demonstrate that engineering decisions at the design stage have direct economic and operational implications, reinforcing the importance of integrating circularity considerations into early design phases. Although the model was developed for the swing drive system of a hydraulic excavator, the structure of the proposed criteria is sufficiently general to be adapted to other subsystems of heavy machinery, such as travel drives or working hydraulic systems. This indicates the broader applicability of the framework across different engineering domains. Future research should focus on further improving the methodology by incorporating real operational data, expanding the set of evaluated alternatives, and validating the model through expert-based and data-driven approaches. In addition, the integration of fuzzy AHP with advanced methods, such as machine learning or hybrid MCDM techniques, represents a promising direction for enhancing the accuracy, adaptability, and practical applicability of decision-support models in the context of circular economy-oriented engineering design.

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