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Identifying and evaluating sustainability risks in circular business models: Empirical insights from the heavy equipment manufacturing industry

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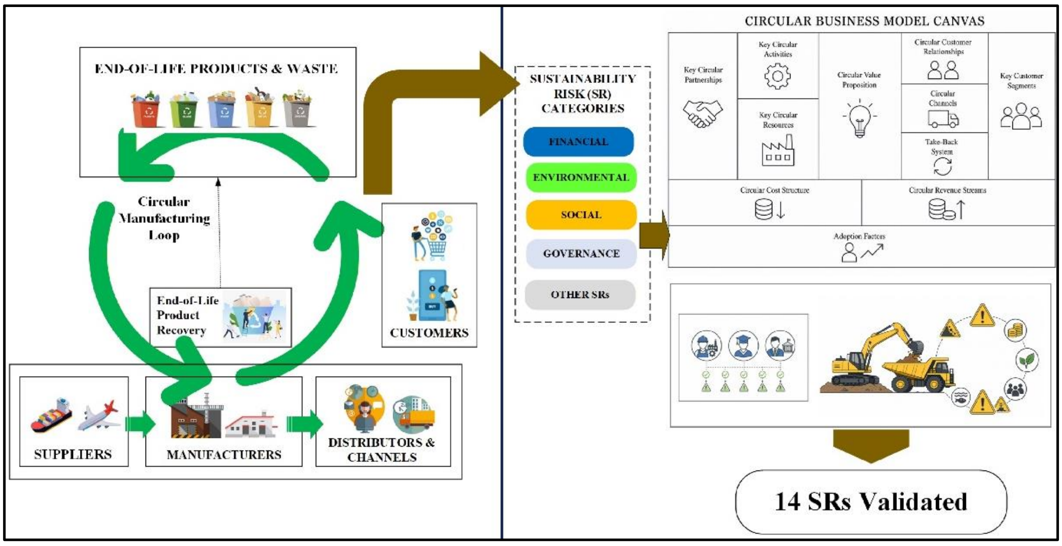

Highlights:

- Sustainability risks were systematically identified and mapped using a circular business model canvas across four heavy equipment and industrial machinery manufacturing firms.
- Fuzzy Delphi Method was used to validate the relevance of sustainability risks.
- OH&S (Occupational Health and Safety) hazards and misjudged End-of-Life component quality are the most critical recovery risks.
- The validated risk set shows that sustainability risks in circular business models are predominantly operational and technical.

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Abstract

Circular business models (CBMs) are increasingly being adopted in heavy equipment manufacturing to extend the value of end-of-life (EoL) components through recovery practices. However, existing sustainability risk assessments largely rely on generic literature-based risk lists without verifying their contextual relevance to specific industries. This study addresses this gap by systematically exploring and validating sustainability risks that are specifically relevant to circular manufacturing in the heavy equipment sector. An initial set of 32 sustainability risks was identified through literature review and cross-industry exploration. These sustainability risks were then evaluated using the Fuzzy Delphi Method (FDM) to manage uncertainty and establish expert consensus on their relevance to circular business models in the heavy equipment manufacturing sector. Based on the consensus criteria (d ≤ 0.2; agreement ≥ 75%), 14 risks were validated as contextually relevant. The findings reveal that the most critical risks are concentrated in key circular activities, particularly those related to occupational health and safety hazards in EoL component recovery, and inaccurate or insufficient evaluation of the quality of components or products to be recovered. The main contribution of this study lies in moving beyond generic sustainability risk identification toward context-specific validation of sustainability risks in circular manufacturing. By filtering and confirming sustainability risks that truly reflect industrial realities, the results provide a robust foundation for targeted sustainability risk assessment and mitigation. Practically, the validated sustainability risk set provides decision-makers and engineers with a more precise basis for prioritizing sustainability risks and enhancing the resilience of circular manufacturing systems.

Keywords: Sustainability risks; Decision analysis; Fuzzy delphi; Circular manufacturing; Heavy equipment

1. Introduction

The global population is projected to reach around 10 billion by 2060, which will continue to increase demand for products and put additional pressure on manufacturing activities [1]. As population size grows, it becomes a key driver of industrial expansion, especially in the manufacturing sector, by intensifying demand for manufactured goods and related services [2], [3]. This rising consumption inevitably generates larger volumes of end-of-life products, which in turn accelerate the depletion of natural resources, increase waste generation, worsen environmental pollution, and raise concerns.

In line with the phenomenon mentioned, the consumption of natural resources has been growing significantly over several decades, reaching 90 billion tons per year. It is predicted to continue to increase, doubling by 2060 [4]. The USA, China, India, Brazil, and Indonesia are the world's largest producers of waste, so they need greater stakeholder efforts to implement waste management strategies [5]. Addressing these intertwined challenges requires the implementation of circular economy principles. By extending product life cycles and recovering value from industrial waste streams, circular strategies improve resource efficiency, alleviate environmental pressures, and facilitate the transition toward more sustainable industrial development. As natural resources are depleted, global warming intensifies, and demands for superiority compete, the transition to a circular economy becomes all the more critical [6]. Researchers and practitioners agreed that circular business model solutions can increase profits while repairing the environment by reducing waste [7]. This model addresses the problem of industrial waste while simultaneously minimizing the large-scale exploitation of natural resources.

Circular industries have the potential to reduce emissions while simultaneously creating new income opportunities for circular economy practitioners [8]. A circular production and consumption model can extend the product life cycle at end-of-life, thereby increasing the value of more products [9]. In the European Union, the circular economy approach can save hundreds of billions of dollars by reducing procurement costs for materials, providing significant environmental benefits [10]. EMF predicts that an economic circular can save $700 million in material costs and reduce emissions by 48% by 2030 [11].

In the mining-equipment industry, the adoption of a circular economy through remanufacturing heavy machinery can achieve substantial environmental and economic benefits. For example, the environmental impact of remanufacturing mining machinery reports that remanufacturing components of mining machinery may reduce global warming potential by ~110,000 tons CO_2-eq per year when scaled globally [12]. Beyond environmental benefits, remanufacturing enhances profitability: according to the Evaluation of environmental impact and benefits for remanufactured construction equipment parts using Life Cycle Assessment [13], remanufacturing heavy-equipment parts may yield profits up to USD 2.3 million per year. Despite these prospects, the remanufacturing industry confronts several significant challenges, notably reverse logistics, which continues to be a major barrier for heavy-vehicle and heavy-equipment manufacturers [14].

Despite these substantial environmental and economic benefits, the implementation of circular economy practices in the remanufacturing industry poses several significant challenges. Dynamic environments and uncertainty are critical issues in the circular economy business model, underscoring the importance of risk mitigation [15]. Risk management is a crucial factor in achieving a sustainable circular business model [16]. Throughout 2022–2023, the World Economic Forum (WEF) examined perceptions of global risks that had previously materialized and their impacts [17]. The results (**Figure 1**) indicate that, in the long term, environmental and social risks are perceived as the most frequent and significant categories of risk. Given this pattern, risk identification should explicitly incorporate environmental, social, and other factors that promote sustainability. Accordingly, risks that simultaneously affect environmental integrity, social well-being, and economic performance can be conceptualized as sustainability risks, which are defined as potential events or conditions that threaten the achievement of long-term sustainable development objectives across these interrelated dimensions [18].

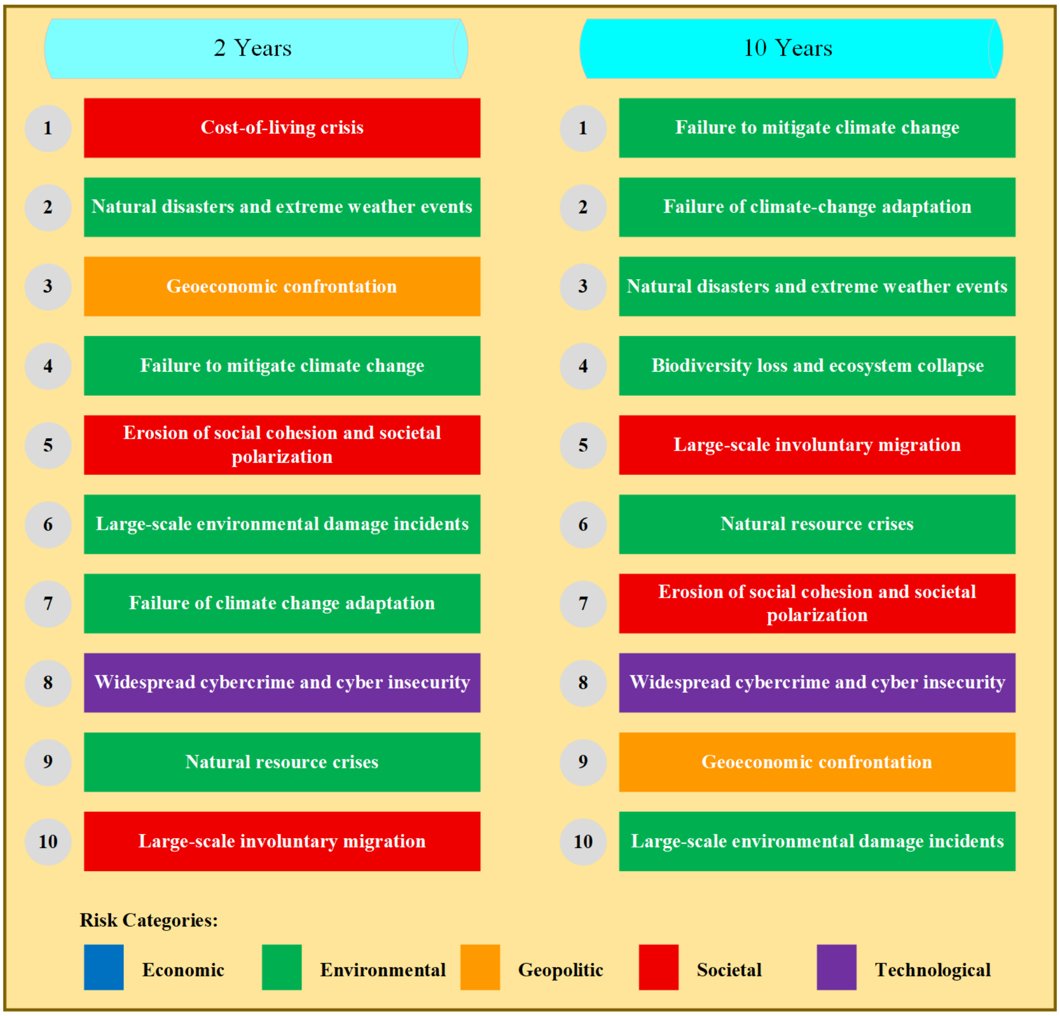

Figure 1. Global risks based on severity in the short and long term [17]

The industry must address sustainability risks; however, there is currently limited research on evaluating sustainability risks [19]. Sustainability risks affect a system's overall sustainability and pose significant threats to organizational performance [20]. A lack of attention to these risks further increases organizational vulnerability, highlighting the need for a structured framework to manage sustainability risks effectively [21]. Existing studies on sustainability risks in supply chains provide an important foundation for examining such risks in both supply chain and manufacturing contexts [22], [23], [24], including manufacturing industries that use circular principles. However, research specifically addressing sustainability risks within circular business models remains limited, despite its high relevance and substantial potential for further development [25], [26].

Numerous studies have identified sustainability risks associated with product development in manufacturing companies [27], [28], [29]. Recent studies emphasize the importance of assessing and managing sustainability risks in manufacturing systems with multiple stakeholders, encouraging the development of more comprehensive frameworks building upon previously established risk management models [24]. However, existing studies largely confine sustainability risk analysis to the product development and design stages, framing risk as a product-level issue rather than a systemic business model concern. Sustainability risk assessment in mechanical design has mostly been examined at the conceptual design stage, but comprehensive evaluation at the circular business system level is still underexplored [30]. Recent studies on sustainability risk assessment have examined copper mining projects by evaluating risks across economic, social, and environmental dimensions [31]. However, these analyses remain confined to project-level assessments and do not comprehensively capture the practical risks embedded within real industrial business models. Consequently, limited attention has been paid to how sustainability risks are structurally incorporated throughout the full configuration of circular manufacturing business models, including partnerships, resource loops, reverse logistics, value capture mechanisms, and institutional dynamics. This limitation constrains a systemic understanding of risk propagation within circular manufacturing, highlighting the gap addressed by this study.

Sustainability risk studies on recycling in heavy engineering have been conducted and are relevant to circular manufacturing; nevertheless, they are typically confined to highly specific sectors with unique risk contexts, limiting their broader transferability [32]. Although some studies adopt a systemic perspective by integrating sustainability dimensions, their analyses remain focused on particular projects or operational segments rather than the circular manufacturing business model as a whole. As a result, sustainability risks have not been comprehensively identified across the full configuration of the circular manufacturing business model. Moreover, limited research has examined sustainability risks in circular business models that recover OEM components within the heavy equipment sector [14]. Addressing this gap, the present study systematically identifies and evaluates the relevance of sustainability risks within heavy-equipment circular manufacturing business models.

Approach technique based on integrating Fuzzy with several methods beyond those used in studies on sustainability risk [19], [32], [33], [34]. The Fuzzy DEMATEL method was used in [32] to handle complex problems by mapping causal linkages between consequences and relevant risk factors. Meanwhile, in the research, the ANP (The Analytical Network Process) method is used to integrate sustainability into risk management to combine and measure dependence between criteria without the need for hierarchy [35]. The study employed the Fuzzy Synthetic Evaluation (FSE) method due to its capability to address complex systems, accommodate sampling uncertainty, and operate without strict minimum sample size requirements [33]. However, these methods are more appropriate for structuring and prioritizing predefined risk factors in relatively stable decision contexts than for inductively exploring sustainability risks in emerging circular manufacturing business models, where risk categories and configurations are still fluid and evolving.

The Delphi technique is also widely used by many researchers and others. According to Häder [36], the Delphi Method can use consensus among experts to aggregate ideas and determine non-specific objects. Compared with focus group discussions (FGD) and interviews, the Delphi method has several advantages: it operates effectively with relatively small expert panels, ensures participant anonymity to reduce dominant bias and social desirability effects, and allows experts to revise their judgments based on controlled feedback from other panel members [37]. However, the conventional Delphi method may result in low convergence, information loss, inconsistent expert judgments, and a prolonged research process; therefore, integrating a fuzzy approach is necessary to achieve more consistent and reliable results [38]. In settings where conventional statistical models are infeasible due to missing data, the Delphi method, when generalized with fuzzy sets, effectively addresses ambiguity and uncertainty [39]. Integrating fuzzy logic into the Delphi method enhances the analysis of inherently uncertain phenomena by systematically engaging experts and stakeholders, making it well-suited to address risk uncertainties in Indonesia's nascent circular-economy implementation. As a result, this study uses the Fuzzy Delphi approach to identify and prioritize sustainability risks for circular product manufacturing business models.

2. Methods

This study was conducted in several stages, as described in **Figure 2**. This research is structured into three main phases: (1) a literature review to identify sustainability risks in circular manufacturing business models; (2) an empirical study involving semi-structured interviews with industry practitioners to explore sustainability risks in manufacturing; and (3) an evaluation of sustainability risks based on their relevance to circular manufacturing business models in the heavy equipment and machinery sector.

2.1. Scoping and Initial Screening of Sustainability Risks in Circular Manufacturing Business Models

The term "circular business model" refers to the Business Model Canvas, which was developed as a result of a previous study on business model circularity [40], [41]. The business model canvas was selected due to its well-established application in industrial settings, particularly in manufacturing contexts that adopt circular practices. It serves as the reference model because of its suitability for industries implementing circular economy principles, especially in manufacturing.

The elements of the take-back system and adoption factors identified by Lewandowski [40] were incorporated into the design of Pollard *et al.* [41] because they are essential to the success of circular manufacturing business models, particularly those under development. The framework was subsequently modified to align with the research objectives, as presented in **Figure 3**.

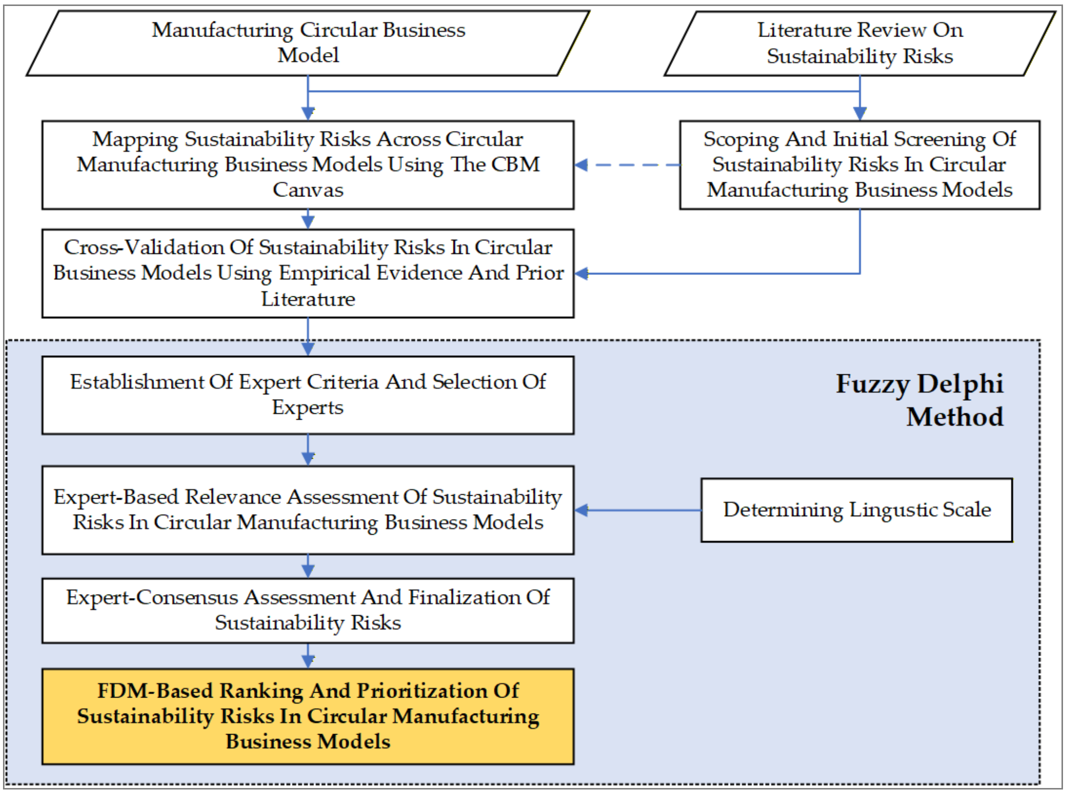

Figure 2. Research flow diagram illustrating the study's stages

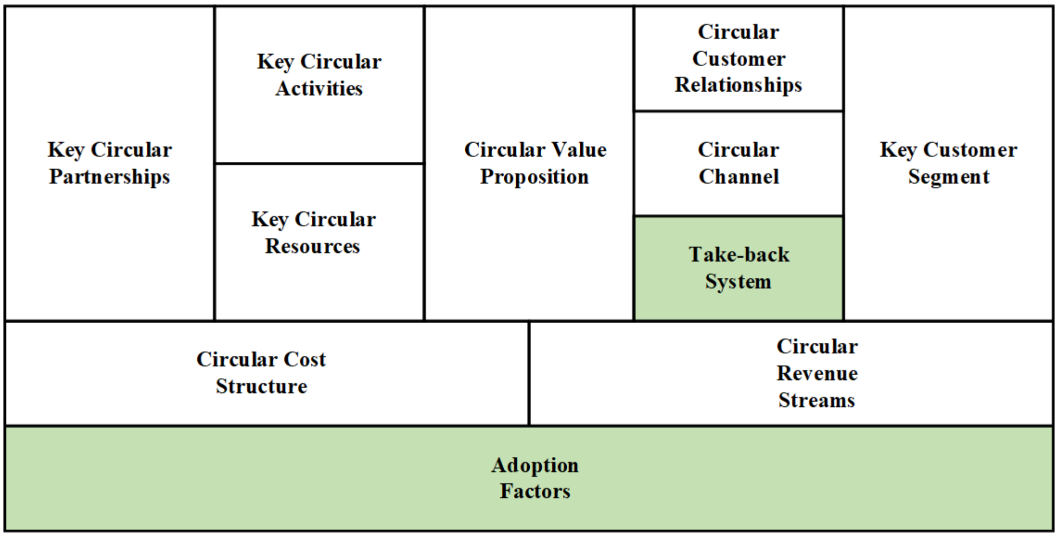

Figure 3. Modified circular business model canvas adapted from [40] and [41]

2.2. Map Sustainability Risks Across Circular Manufacturers Using the CBM Canvas

Empirical data were collected through open-ended, semi-structured interviews with experts from four manufacturing firms engaged in original equipment manufacturer (OEM) component and product recovery in the heavy equipment and machinery sector. The interviews were designed to systematically identify potential sustainability risks in alignment with the circular business model framework adopted in this study. The company profiles are summarized in **Table 1**.

Table 1. OEM manufacturing industry company profile

Category	Company 1	Company 2	Company 3	Company 4
Year of Establishment	1997	1994	1998	1997
Organizational structure	Official representative from International Companies	It is a holding company of international companies	The company is located under the parent company that has gone public.	Joint venture between a multinational company and a national company
Global Employees	> 54,000 employees	> 13,000 Employees	11,000–15,000 employees	>800 employees
Company Types and Services	Heavy equipment, such as mining excavators, PR-series dozers, off-highway trucks, mobile & crawler cranes, as well as component mechanical and hydraulic systems	Gas and steam turbines, Compressors, Expanders and pumps, high technology, generators, motors, and equipment related to other	Excavator, crane, dozer, distribution, rental, technical service, training	Remanufacturing company for heavy equipment (dump trucks, bulldozers, hydraulic excavators, etc.)
Activity recovery product or component	Reconditioning of splitter boxes, cylinders, gearboxes, engines, and hydraulic components for heavy machinery	Repair, remanufacturing, and upgrading services for industrial and heavy-equipment components	Component recovery and repair for haulers, excavators, and other mining machinery.	Replacement, remanufacturing, and assembly of engines, cylinders, transmissions, and power modules for heavy equipment

Sustainability risks were subsequently mapped based on expert insights from manufacturers implementing circular economy practices. The interview protocol was structured based on key elements of the circular business model canvas (see **Figure 3**), ensuring conceptual consistency and analytical rigor. This approach allows experts to define sustainability risks grounded in their professional experience while maintaining alignment with the theoretical framework.

2.3. Cross-Validation of Sustainability Risks in Circular Business Models Using Industry Evidence and Prior Literature

After identifying sustainability risks based on empirical observations in heavy equipment component recovery manufacturing, the results were cross-validated with literature findings to establish a set of initial sustainability risks. Sustainability risks found in the literature but not observed in the case companies were excluded from further analysis. Similarly, sustainability risks identified in only one company but not supported by prior literature were also excluded. The analysis, therefore, focused on sustainability risks consistently supported by both the literature and empirical observations. However, risks identified in at least two manufacturing companies but not previously reported in the literature were considered potential new findings and subjected to further examination.

2.4. Fuzzy Delphi Method

The Fuzzy Delphi Method consists of several stages: establishment of expert criteria and selection of experts; determination of the linguistic scale; expert-based assessment of sustainability risks in circular manufacturing business models; expert-consensus evaluation and finalization of sustainability risks; and FDM-based ranking and prioritization of sustainability risks in circular manufacturing business models.

2.4.1. Establishment of expert criteria and selection of experts

In this research, a closed questionnaire was used, involving experts from the practitioner, academic, and research communities. The expert panel was required to have substantial experience in heavy equipment or heavy machinery manufacturing, including practitioners, academics, and researchers, with a minimum of approximately 10 years of relevant industry experience to ensure the credibility and validity of their judgments [42], [43]. Most experts were practitioners, so that the identified sustainability risks would be operational, technical, and closely aligned with real industrial conditions, while the total of nine experts reflects the limited number of manufacturers with mature circular practices, yet still falls within the typical panel size reported for Fuzzy Delphi applications in prior studies [44]. Professional experts are described in the following Table 2.

Table 2. Expert profile

Experts	Title and Position	Type of Company	Length of work
Expert 1	R&D Division Head	Remanufacturing company	21 years
Expert 2	Remanufacturing Manager	Heavy equipment manufacturing	22 years
Expert 3	Manager – Rebuild Center	Mining contractor company	25 years
Expert 4	Director of Sustainability	Industrial engineering services	31 Years
Expert 5	Department Head Remanufacturing Dept.	Heavy equipment distributor	20 years
Expert 6	Supervisor	Remanufacturing company	14 years
Expert 7	Manager	Remanufacturing company	15 years
Expert 8	Researcher	Research institution	10 years
Expert 9	Associate Professor	State university	21 years

2.4.2. Determining linguistic scale

In this study, the Fuzzy Delphi analysis applies Triangular Fuzzy Numbers (TFN) to model expert evaluations, followed by a defuzzification procedure to derive precise quantitative results [45]. At this stage, a small-scale Likert scale is used to evaluate relevance, which is converted into a fuzzy number set $(n1, n_2, n_3)$ with values ranging from 0 to 1. In this study, the conversion of fuzzy number sets to the linguistic scale used by researchers to evaluate risks is shown in Table 3 and Figure 4 [34].

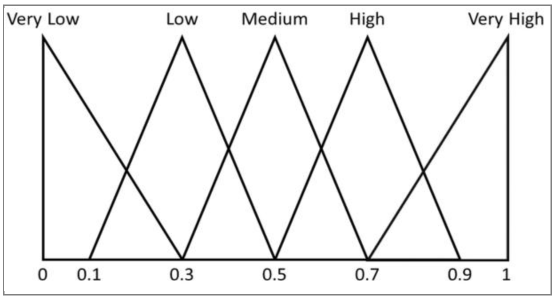

Figure 4. Fuzzy triangular membership functions [34]

Table 3. Linguistic scale level relevance of sustainability risks to circular manufacturing business models

Linguistic Scale	Description	(TFN)
Totally Irrelevant	Has no connection at all with the principles or practices of circular business models.	(0; 0.1; 0.3)
Irrelevant	Has only a slight connection and does not significantly influence the implementation of circularity.	(0.1; 0.3; 0.5)
Moderately Relevant (Neutral)	Has a moderate connection and can partially support aspects of circularity.	(0.3; 0.5; 0.7)
Relevant	Plays an essential role in effectively supporting the implementation of circular business models.	(0.5; 0.7; 0.9)
Very Relevant	Serves as a key element or strategic factor in the circular manufacturing business model.	(0.7; 0.9; 1)

2.4.3. Expert-based relevance assessment of sustainability risks in circular manufacturing business models

After the expert responds to a questionnaire designed based on results validation, the initial sustainability risks identified in interviews are opened, responses are recorded on a Likert scale, and the average fuzzy response is. The formula used in this process is the following:

$$\mathrm{M} = \frac{\sum_{\mathrm{i}=1}^{\mathrm{n}} \mathrm{m_i}}{\mathrm{n}} \tag{1}$$

Information: $\mathrm{m_i}$= value conversion into the fuzzy form that has been given, which reflects the lower limit, the middle value, and the upper limit of the aggregate fuzzy value; n= number of experts.

The M value is usually in the form of a Triangular Fuzzy Number (TFN), namely $\mathrm{m_1}, \mathrm{m_2}, \mathrm{m_3}$, based on n (number of experts).

2.4.4. Expert-consensus assessment and finalization of sustainability risks (The determination of threshold value "d")

Furthermore, based on the values of m and n, a threshold value (d) is determined, and a d-construct assessment is used to determine the stated sustainability risk consensus and is elected for ranking using the formula [46]:

$$d(\bar{m},\bar{n}) = \sqrt{\frac{[(m_1 - n_1)^2 + (m_2 - n_2)^2 + (m_3 - n_3)^2]}{3}} \tag{2}$$

$$d - \text{construct} = \frac{\text{sum of average (d)}}{\text{total experts} * \text{total items in the construct}} \tag{3}$$

Information: $d(\bar{m},\bar{n})$ = Measures the level of difference between two fuzzy numbers (usually two opinions or two fuzzy average values). The smaller the d-value, the higher the level of consensus among experts; m_1, m_2, m_3= Components of the first fuzzy number, representing the lower limit, middle value, and upper limit of the aggregate fuzzy value; n_1, n_2, n_3= Components of the second fuzzy number, representing the lower limit, middle value, and upper limit of an expert's individual fuzzy value.

In general, the Fuzzy Delphi method uses a consensus limit of ≤ 0.2 and a percentage consensus of ≥ 75% for agreed factors. However, the fuzzy approach can still be accepted with a threshold value <= 0.299, which is within the allowed range [45]. This study used a threshold limit of ≤ 0.2 to obtain results with greater consensus, strictness, and validity. Next, selected sustainability risks are ranked for the next stage.

2.4.5. FDM-based ranking and prioritization of sustainability risks in circular manufacturing business models

The defuzzification process determines and prioritizes sustainable risk rankings. In the defuzzification process, the central method gravity (center of gravity) is used to perform defuzzification, namely, to change triangular fuzzy numbers, which consist of a lower limit value (m_1), a middle value (m_2), and an upper limit value (m_3), into a single value [47] using the following formula:

$$DF = \frac{(m_1 + m_2 + m_3)}{3} \tag{4}$$

Information: m_1= lower limit from fuzzy numbers (lower value); m_2= value middle from fuzzy numbers (most likely value); m_3= upper limit from fuzzy numbers (upper value); DF = result defuzzification or crisp value from the fuzzy number.

This formula serves as a basis for practitioners to identify potential sustainability risks for evaluation and further mitigation. It can also be used as a reference for researchers and academics who want to conduct deeper studies on the sustainability risks of circular manufacturing business models.

3. Results and Discussion

3.1. Scoping and Initial Screening of Sustainability Risks in Circular Manufacturing Business Models

A review of internationally reputable journal articles on sustainability risks in manufacturing and risks associated with circular economy implementation was conducted. To the best of our knowledge, no prior study has specifically examined sustainability risks within circular-economy implementation in manufacturing industries. Existing studies tend to frame risks in general terms, despite their inherent economic, social, and environmental dimensions. Accordingly, this study begins by systematically exploring potential sustainability risks from multiple sources, including challenges and barriers to circular economy adoption in manufacturing firms.

The manufacturing industry faces multiple challenges and obstacles while implementing circular manufacturing. In industrial manufacturing contexts where circular business models have not yet been adopted, various uncertainties create challenges and barriers to the transition. Financial and social factors are critical to the effective implementation ofthe circular economy. Financial support from multiple stakeholders [48], high investment costs (including investments in recovery processes), the higher cost of recycled materials, and a lack of awareness of the importance of the circular economy all make its implementation challenging [49]. A lack of skilled experts with the competencies required to implement the circular economy might potentially hinder the transition process [50]. In addition, regulations controlling the circular economy implementation arealso important [51], [52]. Institutions, public entities with regulatory authority, and an informed society are examples of stakeholders participating in circular economy implementation, all of which are critical for sustainable product consumption [50]. Weak laws and regulatory frameworks hinder the implementation of circular economy principles [53]. Furthermore, tax policies can promote and incentivize circular economy implementation [54].

Technology is one of the key challenges that industries must address to implement circular manufacturing [48], [49], [50], [54]. The availability of supporting technologies for developing circular products also poses significant challenges, particularly in developing countries [54]. Time constraints, unmet performance targets, and inadequate logistical facilities all hinder the achievement of sustainable industrial development objectives [48]. The availability and quality of recovery products present challenges in meeting customer demands within circular systems, while insufficient consideration of early product life-cycle stages, especially the design phase, might impede the effective implementation of circularity [49]. **Table 4** provides further details, outcomes, studies, and the identification and exploration of sustainability risks.

3.2. Map Sustainability Risks across Circular Manufacturers Using the CBM Canvas

Open-ended interviews were conducted with experts from four companies operating in OEM manufacturing, heavy equipment, and related industrial sectors. The interview protocol was structured around the circular business model canvas (**Figure 3**), which encompasses eleven elements: key circular partnerships, key circular activities, key circular resources, circular value proposition, circular customer relationship, circular channels, take-back systems, key customer segments, circular cost structure, circular revenue streams, and adoption factors.

The empirical findings indicate that sustainability risks are systematically embedded across these interrelated business model elements. Vulnerabilities arise in key circular partnerships (e.g., dependency, quality variability, and intellectual property exposure), key circular activities (e.g., safety hazards and recovery inefficiencies), and key circular resources (e.g., skilled labor shortages, technological limitations, and material dependence). Market-oriented components, including key value propositions, key customer relationships, circular channels, and revenue streams, are further constrained by price competition, demand uncertainty, and instability in returned product flows, while weak regulatory incentives exacerbate institutional-level risks. **Table 5** consolidates the initial Sustainability Risk Identification (SRI) results across four cases, highlighting structural sustainability risk patterns in circular manufacturing models for recovery-intensive heavy industrial products. The preliminary SRI findings are subsequently validated against the sustainability risks identified from the systematic literature review (SRL). The SRI was then established using empirical findings on sustainability risks.

Thirty-two sustainability risks were identified and assessed for their relevance to the business model of circular manufacturing, which is a specialized industry that involves the recovery of components, OEM manufacturing of heavy equipment, and similar equipment. A relevance assessment was conducted to select sustainability risks that align with the characteristics of the manufacturing industry under study. Using the Fuzzy Delphi method, sustainability risks are assessed by experienced experts involved in this study.

3.3. Expert-Consensus Assessment and Finalization of Sustainability Risks

The previously identified sustainability concerns will be evaluated for their relevance to the business model of manufacturing circular products, with input from research experts. As presented in **Table 6**, fourteen sustainability risks reached the consensus threshold and were selected for ranking to determine the priority sustainability risks. Meanwhile, the remaining 18 sustainability risks did not achieve consensus because the percentage consensus is < 75% or the threshold value is > 0.2.

The results of this empirical study reveal newly identified and more detailed sustainability risks related to the role of partners or third parties within circular business models in the manufacturing industry. Three accepted sustainability risks originate from circular key partnership elements, including: related sustainability risks quality produced partners [SRI1], capacity-limited production to partners [SRI2], and violations of rights created by partners [SRI3]. Four sustainability risks stem from key circular activities elements: namely, danger to health and safety work [SRI4], damage to factory equipment and tools [SRI5], errors in evaluating quality from component end-of-life products [SRI6], and performance and durability of low product quality [SRI7].

Table 4. Identification of sustainability risks based on a literature review

Sustainability Risks	Description of Sustainability Risks	Source
Financial Crisis (SRL1)	Financial crises may disrupt supply chains and raise the prices of energy and raw materials.	[19]
High Innovation Cost (SRL2)	High innovation costs hinder the transition to circular business models.	[55]
High Price of Raw Materials (SRL3)	Rising prices of environmentally friendly raw materials increase production and recovery expenses.	[30], [33], [34], [55]
High Recovery or Operational Cost (SRL4)	Excessive operational and recovery costs limit competitiveness and profitability in circular systems.	[30], [33], [34], [49], [55], [56]
Lack of Investment (SRL5)	Insufficient capital investment constrains the adoption of circular economy practices in manufacturing.	[33], [34], [48], [57]
High Selling Price of Recovered Products (SRL6)	Recovered products sell for higher prices than new components, reducing market competitiveness.	[33]
Unrecoverable Product Waste (SRL7)	Waste products that cannot be remanufactured or recovered contribute to resource inefficiency.	[58]
Lack of Training Facilities (SRL8)	Inadequate facilities for workforce training and development impede capacity building in circular operations.	[29], [56], [57]
Lack of Public Awareness (SRL9)	Low public awareness reduces consumer acceptance of recovered or remanufactured products.	[33], [49], [56]
Occupational Health and Safety Hazards (SRL10)	Workplace health and safety risks may occur in circular business and recovery operations.	[19], [29], [32], [33], [34]
Lack of Workforce Competence (SRL11)	Limited employee competence hinders the effective implementation of circular economy strategies.	[29], [33], [34], [50], [55], [57]
Lack of Industrial Incentives (SRL12)	Insufficient fiscal or tax incentives for circular manufacturing industries discourage participation.	[33], [34], [54], [56]
Lack of Take-Back Regulations (SRL13)	The absence of take-back mechanisms and legal support weakens product return systems.	[33]
Absence of Recovery Policy (SRL14)	No clear company policy exists to support product or component recovery activities.	[33], [34], [51], [52], [56]
Lack of Regulations on RecoveredProduct Utilization (SRL15)	The lack of standards and regulations for the use of recovered products hinders market integration.	[34], [50], [56]
Confidential partner data related to intellectual property (SRL16)	Risks related to the leakage or misappropriation of intellectual property (IP) and proprietary know-how, including confidential information belonging to organizational partners.	[34]
Lack of Technological Support (SRL17)	Limited technological support affects the recovery processes and efficiency of products and components.	[30], [33], [48], [49], [50], [54], [55]
Lack of Technological Understanding (SRL18)	Inadequate understanding of technology limits the comprehensive application of circular economy principles.	[30], [34], [55], [56]
Inadequate Product Collection Facilities (SRL19)	Insufficient distribution and collection facilities for end-of-life products reduce the effectiveness of recovery.	[48]
Inadequate Recovery Infrastructure (SRL20)	Inadequate recovery infrastructure limits the capacity to restore end-of-life products and components.	[19], [33]
Low Quality of End-of-Life Components (SRL21)	Poor material quality of end-of-life components results in low recovery yield and product quality.	[29], [34], [49]
Non-Compliant Supplier Quality (SRL22)	Suppliers and partners that do not adhere to circular standards compromise sustainability performance.	[34]
Unavailability of End-of-Life Products (SRL23)	Lack of availability of end-of-life materials restricts continuous recovery operations.	[29], [34], [49], [56]
Equipment Failure (SRL24)	Frequent equipment failures interrupt recovery or production activities, reducing efficiency.	[55]
Low Product Performance and Durability (SRL25)	Recovered products often show reduced durability and performance compared to new items.	[30], [34]
Low Quality of Recovery Products (SRL26)	Low-quality recycled products lead to customer dissatisfaction and reputational risks.	[33]
Lack of Eco-Design Awareness (SRL27)	Limited consideration of eco-friendly design reduces the circularity and recovery potential of products.	[30], [33]
Delay in Fulfilling Customer Requests (SRL28)	Delays in order fulfillment negatively affect customer trust and satisfaction.	[19]
Failure to Meet Innovation Demands (SRL29)	Failure to meet innovation demands reduces product competitiveness and customer retention.	[19], [29], [34]
Product Competition (SRL30)	Competition from non-circular products threatens the market share of circular solutions.	[57]
Sales Decline (SRL31)	Decreasing sales indicate weak market adoption of circular or recovered products.	[58]
Uncertain Demand for Recovered Products (SRL32)	Uncertain demand for recovered products creates instability in production planning and investment decisions.	[34], [56]

Table 5. Empirical study findings for sustainability risk validation in the heavy equipment and heavy machinery sector

SRL	Empirical findings on sustainability risks	#Com 1	#Com 2	#Com 3	#Com 4	SRI
(1) Key Circular Partnership						
Non-Compliant Supplier Quality (SRL22)	Poor quality performance of third-party partners involved in fabrication and supporting activities for end-of-life (EoL) component recovery that fail to meet company standards.	√	√	√	√	SRI1
-	Limited production or factory capacity of third-party partners supporting EoL component recovery activities.	√	√	-	√	SRI2
Confidential partner data related to intellectual property (SRL16)	Violation of intellectual property rights, design, or product/component specifications by third-party partners engaged in EoL component recovery.	√	-	-	-	SRI3
-	Limitations of access from the principal, technology, and activities main	√	-	-	-	-
(2) Key Circular Activities						
Occupational Health and Safety Hazards (SRL10)	Occupational health and safety hazards in EoL component recovery and related activities, both within and outside the company.	-	√	√	√	SRI4
Equipment Failure (SRL24)	Equipment or machinery failures occurring during EoL component recovery activities.	-	√	√	√	SRI5
-	Inaccurate or insufficient evaluation of the quality of components or products to be recovered.	√	√	√	√	SRI6
Low Product Performance and Durability (SRL25)	Low performance and durability of recovered products.	√	√	√	√	SRI7
Low Quality of Recovery Products (SRL26)	The quality of recovered products does not meet customer expectations.	√	√	√	√	SRI8
(3) Key Circular Resources						
Inadequate Recovery Infrastructure (SRL20)	Inadequate infrastructure and facilities to support EoL component recovery operations.	√	√	-	-	SRI9
Lack of Eco-Design Awareness (SRL27)	-	-	-	-	-	-
Lack of Technological Support (SRL17)	Technological limitations are hindering efficient EoL component recovery.	√	√	√	√	SRI10
Lack of Workforce Competence (SRL11)	Lack of workforce competence within companies performing EoL component recovery.	√	√	√	-	SRI11
Lack of Technological Understanding (SRL18)	-	-	-	-	-	-
Lack of Training Facilities (SRL8)	High investment costs are required for human resource training and skill development.	-	-	√	-	SRI12
Low Quality of End-of-Life Components (SRL21)	Inferior quality of end-of-life components or parts intended for recovery.	√	√	√	√	SRI13
(4) Circular Value Proposition						
Unrecoverable Product Waste (SRL7)	End-of-life product disassembly results in components or parts that cannot be recovered.	√	√	√	√	SRI14
Product Competition (SRL30)	Competitors are providing components or parts at lower prices.	√	√	-	√	SRI15
High Selling Price of Recovered Products (SRL6)	Higher selling prices for recovered products than for competitors' new components.	√	√	-	√	SRI16
(5) Circular Customer Relationship						
Failure to Meet Innovation Demands (SRL29)	Failure to convince customers regarding the value, price, or specification compliance of recovered products.	√	√	-	√	SRI17
-	Complaint from the customer because the product remanufacturing is not in accordance with the request	-	√	-	-	-
(6) Circular Channel						
Delay in Fulfilling Customer Requests (SRL28)	Delays in fulfilling customer orders or recovery requests.	√	√	√	-	SRI18
-	Compliance because No follow the standard	-	√	-	-	-
(7) Take Back System						
Inadequate Product Collection Facilities (SRL19)	Insufficient collection facilities for end-of-life products intended for recovery.	√	-	-	-	SRI19
-	Loss of components during the reverse logistics or retrieval process of end-of-life products or components.	√	-	-	√	SRI20

SRL	Empirical findings on sustainability risks	#Com 1	#Com 2	#Com 3	#Com 4	SRI
Unavailability of End-of-Life Products (SRL23)	Unavailability of recoverable components or waste from end-of-life products.	-	√	√	√	SRI21
(8) Key Customer Segment						
Lack of Public Awareness (SRL9)	Low consumer awareness or willingness to use recovered products.	√	√	-	√	SRI22
Uncertain Demand for Recovered Products (SRL32)	Uncertainty in market demand for recovered products or components.	√	√	√	√	SRI23
(9) Circular Cost Resources						
Financial Crisis (SRL1)	Disturb cash flow, because of excess stock	-	-	-	-	-
High Innovation Cost (SRL2)	High research and development (R&D) costs for product recovery activities.	-	-	√	-	SRI24
High Recovery or Operational Cost (SRL4)	High operational costs are required to meet the quality standards of recovered components.	√	√	√	√	SRI25
High Price of Raw Materials (SRL3)	High price of raw materials needed to achieve near-new quality standards for recovered components.	√	√	√	√	SRI26
(10) Circular Revenue Streams						
Lack of Investment (SRL5)	High investment is required to adopt cost-effective recovery technologies.	√	√	-	-	SRI27
-	Loss of potential revenue due to components that cannot be recovered.	√	√	√	√	SRI28
Sales Decline (SRL31)	-	-	-	-	-	-
(11) Adoption Factors						
Absence of Recovery Policy (SRL14)	Absence of formal policies supporting end-of-life product recovery.	√	-	√	√	SRI29
Lack of Industrial Incentives (SRL12)	Lack of fiscal or regulatory incentives (e.g., tax, import, or preferential treatment) for the recovery industry.	√	-	√	√	SRI30
Lack of Regulations on Recovered Product Utilization (SRL15)	Absence of customer-oriented regulations promoting the use of recovered products.	√	-	√	√	SRI31
Lack of Take-Back Regulations (SRL13)	Lack of regulations governing the collection and retrieval of end-of-life products.	√	√	-	√	SRI32

Within the key circular resources element, two sustainability risks have been identified. First, a lack of workforce competence in companies performing end-of-life (EoL) component recovery [SRI11] limits the effectiveness and efficiency of recovery operations. Second, quality issues arising from the low recoverability of components or products [SRI13] create technical and operational barriers to circular manufacturing practices. In the circular value proposition element, the results of unscheduled demolition activities fulfil standard recovery components [SRI14], which can threaten the company's sustainability, as waste components influence the environment. Furthermore, the activity recovery component of end-of-life products will not provide a profit.

Within the key customer segment element, the inability to convince customers to use recovery service providers constitutes a significant sustainability risk [SRI17]. In addition, end-of-life product disassembly, which results in components or parts that cannot be recovered [SRI18], is recognized as a relevant sustainability risk in circular business models. Within the circular channel element, Delays in executing client orders or recovery requests [SRI8] have been identified as a relevant sustainability risk in circular manufacturing business models. Meanwhile, the unavailability of recoverable components or waste from end-of-life products [SRI21] is recognized as a relevant sustainability risk within the take-back system element. Within the circular revenue stream element, High investment is required to adopt cost-effective recovery technologies [SRI27], which is identified as a sustainability risk that may disrupt the viability of circular business models and threaten long-term industrial sustainability. Fourteen sustainability risks were prioritized as most relevant to circular manufacturing in heavy equipment and machinery industries and framed as top management priorities for assessment and mitigation.

3.4. FDM-Based Ranking and Prioritization of Sustainability Risks in Circular Manufacturing Business Models

Further sustainability risks were ranked based on the fuzzy evaluation scores from opinion experts who had been processed. Visually, the results are shown in **Figure 5**, while the results evaluation is shown in the following **Table 7**.

Table 6. Sustainability risks consensus status based on threshold value and % consensus

No	Sustainability Risks	Threshold (d)	% Consensus	Status
SRI1	Poor quality performance of third-party partners involved in fabrication and supporting activities for end-of-life (EoL) component recovery that fail to meet company standards.	0.20	88.89%	Accepted
SRI2	Limited production or factory capacity of third-party partners supporting EoL component recovery activities.	0.11	100.00%	Accepted
SRI3	Violation of intellectual property rights, design, or product/component specifications by third-party partners engaged in EoL component recovery.	0.20	88.89%	Accepted
SRI4	Occupational health and safety hazards in EoL component recovery and related activities, both within and outside the company.	0.12	100.00%	Accepted
SRI5	Equipment or machinery failures occurring during EoL component recovery activities.	0.15	88.89%	Accepted
SRI6	Inaccurate or insufficient evaluation of the quality of components or products to be recovered.	0.12	100.00%	Accepted
SRI7	Low performance and durability of recovered products.	0.16	88.89%	Accepted
SRI8	The quality of recovered products does not meet customer expectations.	0.18	33.33%	Rejected
SRI9	Inadequate infrastructure and facilities to support EoL component recovery operations.	0.18	33.33%	Rejected
SRI10	Technological limitations are hindering efficient EoL component recovery.	0.19	33.33%	Rejected
SRI11	Lack of workforce competence within companies performing EoL component recovery.	0.07	77.78%	Accepted
SRI12	High investment costs are required for human resource training and skill development.	0.21	77.78%	Rejected
SRI13	Inferior quality of end-of-life components or parts intended for recovery.	0.16	88.89%	Accepted
SRI14	End-of-life product disassembly results in components or parts that cannot be recovered.	0.16	88.89%	Accepted
SRI15	Competitors are providing components or parts at lower prices.	0.17	44.44%	Rejected
SRI16	Higher selling prices for recovered products than for competitors' new components.	0.13	66.67%	Rejected
SRI17	Failure to convince customers regarding the value, price, or specification compliance of recovered products.	0.16	88.89%	Accepted
SRI18	Delays in fulfilling customer orders or recovery requests.	0.19	77.78%	Accepted
SRI19	Insufficient collection facilities for end-of-life products intended for recovery.	0.19	33.33%	Rejected
SRI20	Loss of components during the reverse logistics or retrieval process of end-of-life products or components.	0.23	33.33%	Rejected
SRI21	Unavailability of recoverable components or waste from end-of-life products.	0.20	88.89%	Accepted
SRI22	Low consumer awareness or willingness to use recovered products.	0.16	44.44%	Rejected
SRI23	Uncertainty in market demand for recovered products or components.	0.13	55.56%	Rejected
SRI24	High research and development (R&D) costs for product recovery activities.	0.19	33.33%	Rejected
SRI25	High operational costs are required to meet the quality standards of recovered components.	0.16	44.44%	Rejected
SRI26	High price of raw materials needed to achieve near-new quality standards for recovered components.	0.18	55.56%	Rejected
SRI27	High investment is required to adopt cost-effective recovery technologies.	0.19	77.78%	Accepted
SRI28	Loss of potential revenue due to components that cannot be recovered.	0.21	77.78%	Rejected
SRI29	Absence of formal policies supporting end-of-life product recovery.	0.21	22.22%	Rejected
SRI30	Lack of fiscal or regulatory incentives (e.g., tax, import, or preferential treatment) for the recovery industry.	0.19	33.33%	Rejected
SRI31	Absence of customer-oriented regulations promoting the use of recovered products.	0.13	55.56%	Rejected
SRI32	Lack of regulations governing the collection and retrieval of end-of-life products.	0.18	33.33%	Rejected

Three sustainability risks have the highest ranking in terms ofkey circular activities elements: occupational health and safety hazards in EoL component recovery and related activities, both within and outside the company [SRI4], inaccurate or insufficient evaluation of the quality of components or products to be recovered [SRI6], and low performance and durability of recovered products [SRI7].

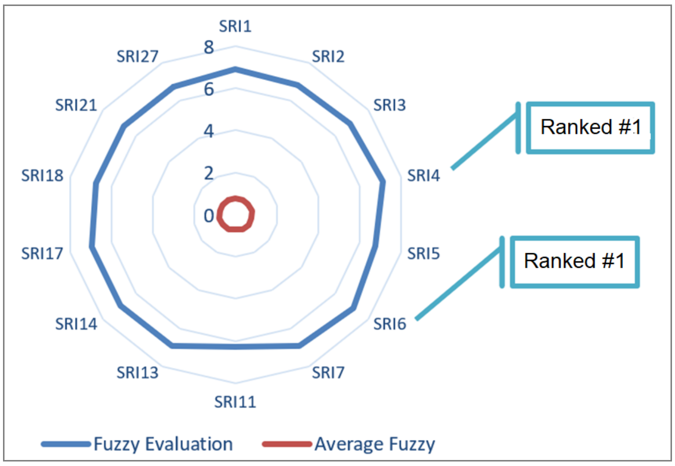

Figure 5. Defuzzification results for prioritized sustainability risks

At the third relevance level, four sustainability risks were identified. Three of them share identical Fuzzy scores: inferior quality of end-of-life components or parts intended for recovery [SRI13], End-of-life product disassembly results in components or parts that cannot be recovered [SRI14], and failure to convince customers regarding the value, price, or specification compliance of recovered products [SRI17].

Table 7. Ranking of sustainability risks

SRI	Fuzzy Evaluation	Average Fuzzy	Ranking
SRI1	6.90	0.77	7
SRI2	6.80	0.76	9
SRI3	6.90	0.77	7
SRI4	7.13	0.79	1
SRI5	6.77	0.75	10
SRI6	7.13	0.79	1
SRI7	6.93	0.77	3
SRI11	6.27	0.70	14
SRI13	6.93	0.77	3
SRI14	6.93	0.77	3
SRI17	6.93	0.77	3
SRI18	6.73	0.75	11
SRI21	6.73	0.75	11
SRI27	6.73	0.75	11

3.5. Discussion

The empirical study of four heavy equipment and machinery manufacturers indicates that key circular activities, key circular resources, key circular partnerships, adoption factors, and circular cost resources are the circular business model elements most exposed to sustainability risks. Several identified sustainability risks originate directly from these core elements, highlighting their central role in shaping risk dynamics within circular manufacturing implementation. Empirical observations revealed the emergence of several new sustainability risks that were not identified in the existing literature. These newly observed risks are limited production or factory capacity of third-party partners supporting EoL component recovery activities, inaccurate or insufficient evaluation of the quality of components or products to be recovered, loss of components during the reverse logistics or retrieval process of end-of-life products or components, and loss of potential revenue due to components that cannot be recovered.The heavy equipment and machinery remanufacturing industry exhibits unique characteristics, particularly in the assessment process of components to be restored. Errors in evaluating the quality and condition of these components may lead to high operational costs and the inability to meet customer requirements.

Nine experts from the industry, manufacturing heavy equipment and heavy machinery similar with experience of more than 10 years, and at the top management level, academics and researchers who are experienced in the industry manufacturing heavy equipment, and application economy circular involved in give evaluation level relevance of sustainability risks to business models manufacturing circular, especially in the industry of heavy equipment and machinery. Based on evaluation level relevance using the Fuzzy Delphi method, 14 sustainability risks are identified, with consensus meeting the standard threshold of ≤ 0.2 and a percentage consensus of ≥ 75%. Most of the sustainability risks identified by experts stem from key circular activities and key circularpartnership elements. Meanwhile, other elements include sustainability risks consensus, key circular resources, circular value proposition, circular customer relationship, circular channel, take-back system, and circular revenue streams.

Circular business models for end-of-life component recovery are very contextual and require geographical validation rather than adopting sustainability risks from a global perspective. The Fuzzy Delphi method was employed to filter sustainability risks relevant to the characteristics of the Indonesian heavy equipment industry. With more than 75% of panelists representing industry practitioners, the consensus results reflect practical realities rather than merely academic perspectives, making them very relevant to decision makers and regulators. The agreed sustainability risks predominantly concern technical and operational aspects of End of Life recovery, including partner quality [19], recovery facility capacity, unavailability of EoL components [33], equipment failure, occupational health and safety [32], workforce competence [29], [55], EoL component quality, failed disassembly processes, investment in recovery technology [55], delays in fulfilling orders, and failure to convince customers [19]. In contrast, rejected risks are mainly associated with macro-level and market policies, such as limited fiscal incentives and regulatory support [56]. These findings indicate that circularity in manufacturing is currently driven primarily by operational concerns.

Based on the ranking of sustainability risks against the established consensus, the two highest-ranked risks are exclusively associated with the key circular activities element. The top two partner-related issues includeoccupational health and safety hazards in EoL component recovery and related activities, both within and outside the company [SR4], and inaccurate or insufficient evaluation of the quality of components or products to be recovered [SR6]. At the third priority level, four sustainability risks emerge from four distinct elements of the circular business model. These include: low performance and durability of recovered products [SRI7](key circular activities), inferior quality of end-of-life components or parts intended for recovery [SRI13] (key circular resources), End-of-life product disassembly results in components or parts that cannot be recovered [SRI14] (circular value proposition), and failure to convince customers regarding value, price, or specification compliance of recovered products [SRI17] (circular customer relationship).

From an engineering standpoint, these operationally oriented risks carry direct implications for mechanical engineering practice in circular manufacturing systems. The consensus on 14 sustainability risks indicates that engineers must extend their focus beyond primary production performance to systematically embed End of Life (EoL) recovery considerations into product and process design. Risks associated with third-party partner quality, limited recovery capacity, equipment failure, and insufficient workforce competence highlight the importance of resilient process configurations, reliability-centered maintenance of recovery equipment, and standardized operating procedures that integrate in-house and outsourced recovery activities.

Moreover, the recognition of inferior EoL component quality and non-recoverable parts underscores the importance of applying design-for-disassembly and design-for-remanufacturing principles at the early design stage. Material selection, joining techniques, tolerancing, and modular architecture should all be designed with future inspection, separation, and reconditioning operations in mind. Finally, the difficulty in convincing customers of the value and performance of recovered products is due to technical challenges: ensuring consistent quality, traceability, and validated performance of remanufactured components. This requires robust testing protocols and quality assurance systems capable of demonstrating functional equivalence with new parts in a credible and verifiable manner.

The research findings provide a practical reference for top management in manufacturing companies implementing circular principles, particularly in OEM heavy equipment and machinery sectors, to systematically identify sustainability risks. This study lays the groundwork for further research, particularly into the linkage between identified sustainability concerns and improved sustainability risk assessment approaches.

4. Conclusion

An analysis of four heavy-equipment and heavy-machinery manufacturing companies shows that sustainability-risk patterns in implementing circular business models are broadly similar, particularly in terms of four elements: key circular activities, key circular resources, adoption factors, and key circular partnerships. Based on the empirical study of four heavy equipment and heavy machinery manufacturers, sustainability risks in circular manufacturing are predominantly concentrated on operational readiness, partner governance, and technical recovery capabilities rather than regulatory or macroeconomic factors. The most dominant risks are operational and technical in nature, including third-party quality issues, inferior EoL component quality, disassembly failures, and equipment breakdowns. These findings indicate that circularity in this industry is currently constrained more by engineering and operational limitations than by external policy conditions.

Assessment using the Fuzzy Delphi Method by nine experts successfully identified 14 sustainability risks that meet threshold consensus (threshold ≤ 0.2; ≥ 75% agreement), many of which originate from elements of key circular partnerships and key circular activities. Sustainability risk with priority highest covering occupational health and safety hazards in EoL component recovery, inaccurate or insufficient evaluation of the quality of components, low performance and durability of recovered products, inferior quality of end-of-life components or parts intended for recovery, and End-of-life product disassembly results in components or parts that cannot be recovered. The prioritization results show that the most critical sustainability risks are predominantly technical and operational, particularly those related to occupational health and safety, quality assessment, component integrity, and disassembly effectiveness in EoL The fourteen validated sustainability risks recovery. This indicates that the sustainability of circular business models in heavy equipment manufacturing is largely determined by engineering robustness and recovery process reliability. Strengthening circular implementation, therefore, requires enhanced safety standards, rigorous quality control systems, and design strategies that improve recoverability and product durability. This study systematically explored sustainability risks from related industries and assessed their relevance to circular manufacturing business models. However, it does not yet provide directly actionable mitigation strategies. Future research should therefore advance toward quantitative risk assessment to support effective mitigation planning. The fourteen validated sustainability risks can be used as structured inputs for methods such as fuzzy AHP, fuzzy synthetic evaluation, and other multi-criteria decision-making approaches to prioritize and quantify risks at the production system, supply chain, and business model levels. Such extensions would strengthen decision support for engineering design and strategic implementation of circular manufacturing systems.

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Authors’ contributions and responsibilities - The authors made substantial contributions to the conception and design of the study. The authors took responsibility for data analysis, interpretation and discussion of results. The authors read and approved the final manuscript.

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