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Enabling Factors for Circularity in the Metal Cutting Industry - With Focus on High-Value Circular Tools

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Abstract. Metal cutting industry, a key sector in manufacturing, is grappling with the transition to a "net-zero industry" to mitigate climate change and reach sustainable practices. Rare and exclusive materials make recycling and reusing cutting tools more pressing and necessitate efficient circular material flows. The purpose of this research is to explore how collaboration can facilitate circularity in the cutting tool industry. It examines the involvement of stakeholders and their roles in achieving a circular lifecycle for cutting tools. To investigate the interaction between metal cutting tools suppliers and Small and Medium-sized Enterprises (SMEs), this study used a mixed-methods approach that includes data from literature, interviews, and document study. Empirical data is gathered to investigate the factors driving circularity and to identify important participants in the lifecycle of cutting tools. The study revealed challenges to the current situation including underutilization of tools due to the absence of a standardization process and subjective operator judgment, as well as lack of traceability of the tools both internally at SMEs and between the stakeholders. Moreover, by mapping the current actors, the study found cutting tool traceability, undirected decision-making throughout tool lifecycles, and limited awareness of circularity dimensions are key challenges. To handle these challenges. 9Rs circular economy framework used to investigate the possible role of collaboration emerges as a vital enabler for circularity, with SMEs playing a significant role. Moreover, the involvement of machine operators, often overlooked actors, is found to be crucial in influencing circular outcomes. Digital solutions and collaborative strategies that involve CNC machine suppliers and intermittent refurbishing business are pivotal in overcoming the challenges identified, namely, traceability and human subjectivity in tool condition assessment. The study demonstrates that technology providers, intermediary refurbishing businesses, SMEs and other stakeholders operating in the metal cutting tools sector must be involved throughout their lifetime to avoid suboptimal results, exchange information, and inspire industrial actors to support the circular economy.

Keywords. Circular behaviours, Collaboration, Cutting tools, SMEs.

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1. Introduction

1.1. Background

Manufacturing firms worldwide are facing a critical turning point in their need to transition towards a 'net-zero industry'. This transformation goes beyond slight, incremental improvements and instead requires a complete overhaul of existing operating processes. Manufacturing is a complex industry, involving large-scale, multi-layered, and non-linear actions [1, 2]. Despite notable advances in recent years, ranging from efficient management practices to technical developments, these advancements are frequently accompanied by significant fossil fuel consumption, energy usage, waste generation, and rising carbon emissions have become synonymous with the manufacturing sector as its traditional icons of innovation and efficiency [3, 4].

Certainly, one of the pressing concerns in this arena is the management of advanced materials, notably those categorised as critical raw materials by the European Union's sustainability policy [5], such as tungsten, vanadium, and titanium. Because of their unique properties, these materials are significant for a variety of purposes in the industrial sector, but they are also a focus in sustainability concerns. The methods used to extract and process these minerals consume a lot of energy and cause environmental issues such as air and water pollution [6]. Simultaneously, the global demand for these resources continues to rise because of population growth and rapid technological improvements. The limited availability of these resources, however, highlights the flaws of our existing strategy and its lack of long-term viability [7]. As a result, handling these materials, including recycling, and reusing them, is an urgent requirement. The essential question is not whether to embrace sustainability in they we manage these materials, but rather how to do so effectively. This is especially important considering the approaching Industry 5.0 paradigm [8].

Narrowing our focus to Sweden, data from the Circularity Gap Report [9] reveals a compelling strategy for fostering sustainability through circularity. According to the report, Sweden could significantly enhance resource efficiency by switching to using robust, long-lasting machinery and equipment in production. According to estimates, such a change may lower the country's material footprint by 5.3% while simultaneously improving its material circularity indicators.

An insightful case study to examine the difficulties and opportunities of handling sophisticated materials sustainably is needed. The cutting tool industry provides an ideal context for evaluating the viability and benefits of implementing sustainability strategies due to its long history of innovation and unrelenting focus on efficiency [10]. Efforts towards a greener economy have led to initiatives aimed at improving product quality, and operational efficiency, extending tool longevity, resource use, and embedding sustainable practices throughout the manufacturing process [11]. Nonetheless, the metalworks industry has considerable challenges, particularly in the areas of waste management and recycling, which are critical for reducing its total environmental effect [3, 12].

The metal cutting industry is crucial to modern economies, but its high energy consumption and significant waste generation often lead to severe environmental damage. Incorporating circular economy ideas into this industry is increasingly regarded as a means of mitigating negative consequences while still maintaining economic sustainability [13, 14]. The focus of this article will be on Cemented carbide and High-speed steel tools, which form around 70% of the global market; these tools are used for milling, turning, drilling and other machining processes [15]. see **Figure 1** and **Figure 2**.

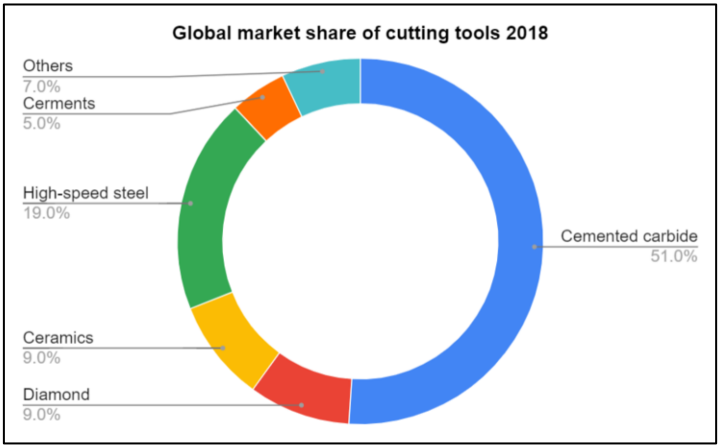

Figure 1. Cutting tools material composition on the global market modified from Rizzo et al., (2020)

Figure 2. Metal cutting tools from the recycling station at a central workshop in Luleå Technical University

Whilst extensive research highlights the importance of circular economy principles like reduction, reuse, and recycling in diverse industries, there is a distinct lack of studies specifically examining these dynamics in the context of metal manufacturing products and equipment [16]. This gap is especially critical when considering interactions between SMEs, metal cutting tools providers, and other stakeholders who may be adopting or creating new technologies to help the metal cutting industrial sector's transition to a circular economy [17-19]. Given the complex dynamics of various stakeholders, each with unique interests in the circular economy environment, few targeted study is a significant problem [20].

Several key factors highlight the necessity for targeted research in this field. Firstly, the complex relationships between SMEs and Metal cutting tools supplier fraught with varied interests and become even more complicated within the framework of a circular economy involving multiple parties [21]. Secondly, the notion of a circular economy must be integrated across the entire lifecycle of metal products, from product and process conceptual design stage to disposal. This comprehensive approach goes beyond most current studies, which frequently focus on discrete elements like energy usage or metallurgy [22, 23]. Thirdly, current research tends to focus excessively on the energy and metallurgical aspects, neglecting other vital dimensions like the role of rare metals in cutting tools [11]. Various studies have identified obstacles to implementing a circular economy in different industries, including the metalworking sector [24, 25]. However, when it comes to metal cutting tools practical solutions are lacking, and the energy implications of digitalisation in a circular economy are not fully explored. Additionally, little attention given to collecting and sharing product lifecycle data, which is essential for circular strategies like remanufacturing that have yet to be fully explored [23, 26]. Additionally, the scarcity of rare metals is a significant obstacle for metalwork industry, particularly for metal-cutting tools as these materials are essential for enhancing the toughness, accuracy, and efficiency of mechanical strength of cutting tools [7]. However, these metals are usually missed by current recycling processes, either because of their minuscule concentrations or because they combine with other materials, that require more purification and refining processes that consume higher amounts of energy, result in elevated operational costs, and ultimately lead to decreased profit margins [13, 27].

This oversight degrades the industry's environmental effect and increases the scarcity of resources. These metals have a limited supply and are geopolitically sensitive, which might impede industrial growth, raise manufacturing costs, and undermine economic stability [28]. As public awareness and regulations around energy use grow, companies risk incurring harsher penalties or operational limits, significantly impacting economic performance [7].

1.2. Problem Statement

The transition to a circular economy in the cutting tool manufacturing industry presents significant challenges, particularly in the realm of multi-stakeholder collaboration. Despite the rising interest in the circular economy, there is a limited understanding of how collaborations between cutting tools providers, SMEs, and intermediary entities could effectively promote circular practices at the user level. This gap inhibits the sector's progress toward sustainable practices and efficient material flows. To bridge this knowledge gap, the following research questions have been formulated.

RQ1: What theoretical frameworks underline metal cutting industry sustainability and circularity collaborations?

This research question lists theoretical findings regarding collaboration in metal-cutting industry to achieve sustainability and circularity. An intensive literature review and snowballing process will illustrate how these concepts apply to this industry.

RQ2: How can collaboration between cutting tool providers and SMEs correspond with circular economy concepts across the product life cycle?

With the theoretical insights from the RQ1, QR2 will be investigated through a case study that will include interviews and document analysis with both tool suppliers and SME users, as well as. The goal is to identify particularly prominent areas in the product life cycle where present collaborations help or hinder circularity in tool use.

RQ3: What practical recommendations might be implemented to improve the circularity of cutting tools within current collaborative frameworks between tools suppliers and SMEs?

Through this research question the theoretical underpinnings of RQ1 is combined with the practical results of RQ2 to offer focused actions. This topic will explain how current partnerships might be maximized to enhance circularity and sustainability through a compilation of best practices, thereby making theoretical knowledge actionable.

2. Theoretical Framework

2.1. Circularity in metal cutting tools context

Efficient metal cutting is an essential component of industrial manufacturing processes. In today's world, it is critical to keep sustainability in mind while carrying out these tasks. The usage of rare metals like tungsten, chromium, molybdenum, vanadium, and cobalt in creating cutting tools is significant. These metals play an important role in discussions regarding sustainability in industry. It is essential to ensure that the manufacturing process of cutting tools does not harm the environment. Therefore, it becomes necessary to focus on using sustainable practices while creating cutting tools. This will ensure that the cutting process is efficient while also preserving the environment for future generations [11, 13, 14]. The requirement for a variety of cutting tools in the performance of various machining activities adds to the difficulty of sustainable tool management. It is typical for a single industrial process to require cutting tools with different metallurgical compositions, and occasionally even multiple brands, adding to the complexities of designing cohesive sustainability policies [29].

Operators intentionally underuse tools to preserve surface quality and reduce mechanical shocks and vibrations.[30]. Remaining Useful Life (RUL) prediction models are one approach to solving this problem, these models address the scheduling of tool refurbishments, maximising tool lifetime without sacrificing operating efficiency [31]. Furthermore, machining parameter optimization based on real-time data and prediction algorithms provides another way to increase the usable life of cutting tools. Such focused changes seek to reduce both the consumption of cutting equipment and operating expenses, in line with the larger sustainability goal [31, 32].

It is a pressing concern that cutting tools are underutilized, with studies showing that they are typically only used for 50-80% of their intended lifespan, resulting in significant resource waste [33]. European and Japanese manufacturers tend to operate at less than or equal to 70% of tool lifespan [34] underutilization of this magnitude always leads in decreased tool life, increased machining costs, and inefficiencies in resource usage. To address this issue, effective approaches for prolonging tool life without losing quality are required [35]. Finally, end-of-life management solutions for cutting tools differ depending on their recyclability. Some tools, due to their crucial dimensions and tolerances, cannot be reconditioned efficiently without impacting the quality of subsequent cuts. High-wear-resistant coatings, for example, provide a feasible, long-term option for these equipment. Conversely, a portion of cutting tools may be reconditioned using processes such as grinding, bringing them more in line with circular economy concepts [35]. The majority of the aforementioned studies have highlighted usability, prolonging product life, and technical solutions as means of promoting sustainability in industrial settings. However, this approach has failed to consider the crucial sociotechnical elements present in shop floor environments. Technical tools do not operate solely, but rather are deeply intertwined with managerial, logistical, and other soft systems. These factors greatly impact the effectiveness and utilization of these tools. A system-oriented approach is essential to understand the relationship between technical solutions, their sociotechnical surroundings, and sustainability outcomes.

2.2. Collaborative approaches to implementing the 9Rs in SMEs

The notion of a circular economy has been subjected to a number of interpretive frameworks, each of which has served to define its fundamental principles with differing degrees of complexity [36]. While the 3Rs (reduce, reuse, recycle) are well-known, expanded frameworks like the 4Rs and 6Rs offer additional insights. The 4Rs introduce 'recover,' focusing on reclaiming energy or materials from waste. The 6Rs add 'redesign' and 'remanufacture' to emphasize sustainable product design and lifespan extension [36-38]. An even broader 9Rs framework exists, capturing strategies for smarter product usage, extended life-cycles, and innovative material applications [38]. However, the 9Rs (Refuse, Rethink, Reduce, Reuse, Repair, Refurbish, Remanufacture, Re-purpose, Recycle, and Recover) offer the most comprehensive perspective, especially in an academic context. This framework presents a lifecycle approach, dividing product management into three distinct phases: acquisition, usage, and end-of-life [38, 39]. The first three Rs (Refuse, Rethink, and Reduce) correspond to the acquisition phase. Collaboration in this area may be especially beneficial to SMEs through collaborative procurement activities and bulk purchasing. This type of collaboration reduces waste and expenses while increasing collective bargaining power, resulting in more responsible production from suppliers [40-42]. The middle set of Rs (Reuse, Repair, Refurbish, Remanufacture and Re-purpose) are focused on the usage phase. Collaboration in this stage can manifest as shared platforms for product use, or as joint ventures in refurbishment centers, often facilitated by technology providers. This allows for mutual knowledge and resource sharing, thus extending product lifespans and enhancing value retention [43, 44]. Finally, the end-of-life phase is encapsulated by the last two Rs (Recover and Recycle), this level necessitates the use of specialist capabilities and technologies, as well as collaborative efforts. Companies might collaborate to invest in recovery facilities or collaborate with technology vendors who supply particular recycling solutions. Furthermore, participants of the supply chain may use reverse logistics systems to better manage end-of-life items, transforming waste into useful input for future products [4, 21]. In summary, collaboration serves as a cornerstone for operationalizing the circular economy practices, fulfilling both economic and environmental sustainability objectives [41, 45].

2.3. Collaboration between technology providers and SMEs

Collaboration is important in the industrial sector and has been widely researched. The interaction between SMEs and technology suppliers is an essential consideration, Suppliers provide SMEs with necessary technological solutions that increase productivity and streamline operations, while SMEs provide a diversified market for customisation and scaling. Issues of power imbalance and trust, however, often complicate this interaction [46, 47]. Co-innovation projects are critical for increasing knowledge and resource sharing across various parties to jointly develop breakthrough goods and technology [20, 48, 49]. Knowledge sharing and transfer is a critical method for reciprocal learning that results from collaborative creative activities. This constant exchange of knowledge frequently leads to joint R&D ventures, a strategic alliance that allow SMEs and technology suppliers to share expertise, risks, and expenses involved with innovation [1, 50]. Therefore, Tailored Technology Adoption Programs are merging as a succeeding strategy as technology vendors offer solutions to easily incorporate new technologies into SME operations [28, 51]. The potential for using Data Analytics and Insights is clear here, allowing SMEs to reap the benefits of data-driven decision-making in strategic planning and product development [17, 52]. Supply Chain Integration manifests as a crucial focal point, particularly in the domain of IT systems, as part of this data-enabled approach to maximise logistical and operational efficiencies. Furthermore, given the quick improvements in technology, Training and skill development programs are becoming increasingly important, and are frequently planned and provided by technology suppliers to keep SMEs' workforce up to date on technological evolutions [53, 54]. Strategic Planning and Roadmapping bring the relationship between SMEs and technology suppliers full circle, aligning their various yet linked objectives for sustainable innovation and market competitiveness [41, 55].

3. Methodology

3.1. Data collection methods

The study focuses on two organisations: Company X is a SME in southern Sweden that specialises in automotive spare parts, and Company Z is a significant global producer of tungsten carbide-coated metal cutting tools. Semi-structured interviews with various managerial and technical roles were undertaken, guided by an interview protocol translated from Swedish and back to English. Secondary data were collected through thematic analysis of internal files related to buy-back programmes implementation strategies [56]. Data in the form of interview transcripts was used in the subsequent analysis.

3.2. Literature review

In addition to the initial focused literature review, a more comprehensive review was carried out using databases such as Scopus and Web of Science. Keywords used included "collaboration," "SMEs," "circular economy," "sustainability," and "cutting tools." An initial search found 147 articles, which were reduced to 40 after selection criteria were applied. Through snowballing, an additional 10 papers were added, resulting in a total of 61 articles for the literature review.

3.3. Data analysis

The data analysis procedure was aided by NVivo software, which included coding and theme analysis of both interview transcriptions and company documents. This strategy facilitated in the discovery of recurring patterns and themes, which were then validated by comparison with existing literature [57]. Data triangulation was accomplished by combining information gleaned through interviews, document analysis, and a review of the literature. This multi-method approach promotes a more comprehensive and nuanced understanding, which improves the validity and dependability of the study findings [58]. The study used Framework Analysis, as established by Ritchie and Spencer [59] for the qualitative analysis, which is particularly appropriate for policy research and other applied disciplines needing structured yet adaptable analytical processes. The following analysis process was followed:

1. Familiarisation: An first review of interview transcriptions offered a thorough understanding of the dataset.
2. Thematic Framework: This framework was created based on essential topics such as collaborating partners, core competencies, and obstacles.
3. Coding: Extensive coding was used to categorise data extracts according to previously determined topics.
4. Data was condensed into theme charts to allow for cross-participant comparisons.
5. Mapping and Interpretation: In this step, the patterns and associations were contextually analysed in relation to the study topics.
6. Report Creation: A comprehensive report was written, relating empirical facts back to the study questions and supported by statements from participants.

3.4. ToolTrace Project as a research context

This study is part of the ToolTrace project, which aims to promote sustainable manufacturing practices in Sweden. The project's goal is to develop a decision support system that encourages efficient recycling and utilization of used cutting tools. Machine operators, researchers, technology providers (Swedish cutting tool supplier), SMEs that will use the system are among the stakeholders. Machine operators adopt circular practices, offering input to help the system develop. The system's success in encouraging circularity will be assessed by researchers. Providers of technology provide their technical skills and resources to increase the system's industrial relevance. SMEs are critical for putting the study's conclusions into practice [60].

4. Findings

4.1. Empirical data highlights

To answer QR2 the findings from document analysis and interviews explain cutting tool life cycles, operational efficiency, and stakeholder incentives and obstacles. **Table 1** shows how tools are acquired, used, and disposed of and emphasizing circularity practices. **Table 2** highlight that quality and time are crucial to operational efficiency. Table 3 shows how circular actions improve the environment and economy while resolving cost and knowledge limitations. These tables serve as a lens to explore the delicate interplay between the many stages of tool life cycles, quality considerations, and stakeholder incentives and obstacles. They represent a reality created not merely by economic imperatives, but also by increasing environmental consciousness and technical limits.

Table 1. Cutting tools life cycle.

Quotations	Code	Theme
"The period varies for the material, depending on what kind of material we have". "We talk to either the person we order through paperwork". "The seller sent an email to customer service and asked what the price is this month". "Sometimes we borrow special tools from other companies if we need".	Acquiring Tools	Life Cycle
"We change when it gets worn out". "We have the program setup ready in the machine to use the tools". "We change it when we have a rough surface". "When the colour of the tool changes then we know"	Usage and Reusing Stage	
"There were three sorting boxes We Melt it down make a new tool and Just reuse the material". "We have two ways to recycle carbide today. After all, we have a mechanical way and a chemical way".	End of Life Stage	

Table 2. Operational Efficiency

Quotations	Code	Theme
"We focus on Cutting properties when we order". "we change the tools when". "when there is a little strange color on a drill then you can change". "we change when It is heard on the sound".	Quality of the Tools	Logistics and Supply Chain
"There is no time on setup the tools when it comes to resharpened or new tools". " I want a preferably new tool or very good tool". "The time span vary for the material depends on what kind of material we have".	Time and Efficiency	Efficiency and Process

Table 3. Motivation and Challenges

Quotations	Code	Theme
"It's about economics. Today there is no shortage of raw material, but from a price perspective, it's beneficial to recycle material" "it is much cheaper to use recycled material"	Economic Motivations	Motivation and Challenges
"Some customer, it's very important that we use environmentally friendly processes as possible". "Reduce consumption of the tools considering, for example, the environment". "Most people say CO_2 and that's because it's very easy and conventional, but here is something else. What chemicals are used, how much water is used"	Environmental Motivations	
"Sorting and changing the tools A lot of times it's probably just a cost". "In the past, customers could easily regrind our metal cutting tools but it is not easy now because of complex inserts". "Do we add value to the regrind or do we just add a cost?". "when customers send the material to us, they do not know that it is classified as waste or hazardous waste"	Challenges	
"I don't know how long I've been running" "I don't know the pros and cons for circular concept" "I don't know much about circular tools". "Someone takes the tools but I don't know where".	Knowledge Gap	

4.2. Circular Actions and Supply Chain Dynamics

The supply chain for cutting tools operates through a combination of pull and push mechanisms. SMEs are the primary drivers of pull, as they create demand for new tools and collect worn-out ones for recycling or refurbishing. SMEs also share highly specialized tools, with other SMEs for high-demand products rather than standard products, such strategy not only improves resource utilization, extending their lifespan and minimizing downtime but also promotes circular behaviour inside the SME network. Push forces come from tool manufacturers and distributors, who introduce new products to the market, and resharpening companies, who restore tools or route non-refurbishable ones to manufacturers for recycling, (see Figure 3)

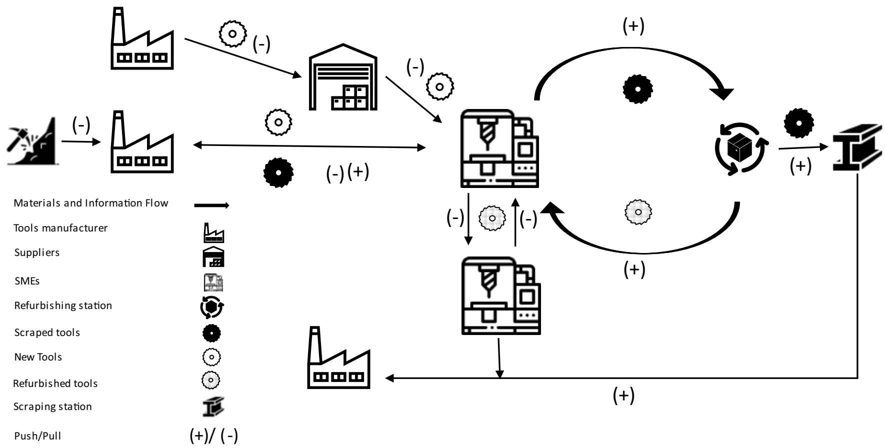

Figure 3. Material and information Circular flow (authors)

The 9Rs of the circular economy are present in this supply chain, as SMEs lend specialised equipment to one another (reusing and sharing), resharpening firms fix and refurbish tools (repair and refurbish), and manufacturing companies recover non-repairable tools to extract valuable tungsten (recycle and recover). However, there is an opportunity for development in areas such as waste reduction and the refusal of unneeded products. Overall, the pull-push dynamics allow pro-circular behaviours and reveal prospects for additional sustainability improvements.

In the context of pull and push dynamics within the supply chain of cutting tools, distinct roles and influences can be observed. SMEs instigate pull dynamics by initiating the demand for new cutting tools, thereby setting the supply chain machinery into action. This demand-pull is complemented by another pull mechanism, activated when SMEs accumulate worn tools and engage recycling companies to manage excess inventory. On the other side of the spectrum, push dynamics are manifested primarily through tool manufacturers and distributors who cater to market demands by directly supplying products to SMEs or via retail channels. Furthermore, resharpening companies execute another form of push by either returning refurbished tools to SMEs or redirecting those that cannot be repaired towards recycling or the original manufacturers.

5. Discussion

As we transition into the discussion part of this paper, we'll shift our focus from simply pointing out problems to actively exploring solutions. The research identified existing gaps, notably in 'Refuse' and 'Reduce' strategies, while also identifying the importance of SMEs and resharpening enterprises in activities such as 'Reuse,' 'Repair,' and 'Recycle.' The following table serves as a strategic matrix, connecting the 9Rs of circularity with collaborative techniques. It intends to steer our conversation from issue identification to prescribing concrete circular collaboration strategies, while addressing the obstacles and possibilities previously identified. See **Table**

Table 4. Recommended circular collaboration strategies.

9Rs	Challenges	Integrated Solutions (Manufacturers, SMEs, Intermediaries)
Refuse	Traceability issues	Start common IoT methods developed by CNC and cutting tool makers; SMEs and intermediaries validate and comply.
Reduce	Human judgement variability	Standardize evaluative criteria and use machine learning-augmented diagnostics from manufacturers and CNC solutions providers backed by SMEs and intermediaries' real-world tests.
Reuse	Operational inefficiencies	Embrace multi-purpose tooling designed collectively, while SMEs adopt rigorous inventory audits to prioritize component reuse.
Repair	Quick tool replacement	Manufacturers offer modular and repairable designs; intermediaries handle logistics, while SMEs commit to scheduled maintenance regimes.
Refurbish	Lack of refurbishing	Manufacturers provide refurbishing instructions, which are supported by intermediaries; SMEs set internal refurbishment goals.
Remanufacture	Waste management	Manufacturers and intermediaries collaborate on service offerings and logistics; SMEs integrate remanufacturing strategies.
Repurpose	Short-term operational vision	Collaboratively design items for simple reusing; SMEs include repurposing into strategic planning.
Recycle	Obstacles in recycling	Create multi-stakeholder recycling databases; SMEs implement rigorous standards recycling processes.
Recover	Absence of long-term sustainability	Stakeholders should work together to create a broad, industry-wide strategy that emphasizes the adoption of circular practices, SMEs to establish internal plans aimed at maintaining these circular practices for the long run. Ex (advanced sorting systems for scrapped cutting tools, Supportive reverse logistics and attractive business agreements).

5.1. Challenges of Operationalizing Circularity

Table 4 presents an innovative framework that integrates the 9Rs of circularity with various forms of engagement between SMEs and technology suppliers. Its goal is to make circularity practicable as well as theoretically sound. However, adopting this approach on the ground presents numerous operational and decision-making challenges.

Traceability, or the ability to track the usage and condition of cutting instruments, is one challenges that arises. It is challenging to develop a consistent, circular system since traceability varies greatly across different tool models and sizes. Even inside organizations, there is variation, and the lack of standardized ways to monitor at scale makes it harder to keep track every cutting tool in every line [8].

This can be a significant barrier for SMEs because they may lack the means for advanced tracking systems, resulting in poor or even wasteful practices [28]. Furthermore, the subjective character of human experience and judgment in tool condition monitoring adds another level of complication. Individual experience can affect their Operators' competence and judgment in detecting tool wear and tear may differ, generating variability that weakens the repeatability and reliability of sustainable procedures. This subjectivity may also result in premature tool replacement and hazardous work circumstances, further distancing organizations from circularity ideals. In light of our findings, there is a compelling need to extend our knowledge on the behavioural intricacies at the shopfloor level. Until now, the conventional view of the shopfloor has been limited to the notion of blue-collar workers performing pre-established procedures. However, we strongly advocate for a different perspective - one that considers the shopfloor as an 'arena' brimming with dynamic possibilities for exploring the impact of human-technology interactions on achieving objectives within the circular economy.

5.2. SMEs: Key to Circular Futures

While equipment suppliers such as CNC manufacturers contribute considerably to value chain creation, our case study revealed that their role in the circular economy is typically marginal. The participation of these stakeholders in the creation and implementation of circular strategies, on the other hand, has the potential to considerably enhance the overall system. Their technology expertise could give novel solutions to problems like tool traceability, condition monitoring, and resource optimization, closing the loop in the 9Rs of circularity. To truly realize this latent potential, SMEs must be involved in the early stages of service and solution development initiatives. Given that SMEs account for a sizable share of the industrial sector, they play a critical role in accelerating the transition to circularity [20]. Their requirements are frequently diverse, moulded by both operational restrictions and business objectives, which, if neglected, may result in gaps in the adoption of circular models. Technology suppliers may ensure that services and solutions are customised to address these specific needs by involving SMEs early on. Early-stage participation of SMEs also serves another important reason: it allows for the integration of both technical and economic perspectives into the development process [51, 52]. SMEs can provide real-world insights into operational challenges such as material flow, waste management, and resource use. They can assist in identifying operational bottlenecks that technology solutions should seek to address. SMEs can provide insights on cost structures, market demands, and competitive challenges from a business standpoint [52]. Their participation assures that the solutions created are not only technologically advanced, but also commercially feasible and scalable. Thus, even though SMEs often adopt efficient, circular solutions due to resource constraints, his this can incentive innovation, optimizes resources, and supports focusing on value added and circular actions. Focus groups, prototype testing, and iterative feedback mechanisms can all be used to facilitate collaboration with SMEs. These approaches enable a more agile development process that can respond to evolving demands and problems, resulting in a more robust and inclusive end product. SME participation in early-stage development aligns with the strategic interests of technology providers. It promotes a mutualistic relationship in which SMEs profit from tailored, effective solutions and technology suppliers get access to a larger market share and a better grasp of industry-specific difficulties. This synergy is consistent with the circularity concept, as it promotes sustainability while also boosting economic viability.

5.3. Concluding remarks - Towards a Holistic Circular Economy

Our proposed approach to achieving a circular economy involves different levels of alignment with the 9Rs. It is worth noting that while 'Refuse' and 'Reduce' actions are underrepresented, 'Reuse' is facilitated through SMEs sharing specialized tools with other organizations. The resharpening companies also play a crucial role in the 'Repair' and 'Refurbish' categories, which reduces the need for new tools, that can be a challenge. Additionally, recycling worn tools and recovering tungsten through buyback programs contributes to a more sustainable, circular tooling ecosystem. However, there are still untapped opportunities for incorporating additional Rs, such as 'Refuse' and 'Reduce,' which require further exploration.

In shop floor day to day operations, the state of cutting tools is not fixed. It changes constantly and affects the efficiency and sustainability of the process. By making agile decisions, adjustments can be made in real-time to machining protocols based on the current condition of the tool. This ensures that tools are used optimally. Automation can help refine this process by determining the best time to resharpen or replace tools across different production lines [33].

In addition, data-sharing capabilities can improve Just-In-Time (JIT) manufacturing strategies, making the supply chain more efficient. This creates a push-pull dynamic that improves both forward and reverse logistics. By adopting this approach, all stakeholders in the value chain can benefit from increased efficiency and sustainability, taking steps towards a more circular economy [41].

The successful implementation of these technical and managerial solutions in SMEs depends on a supportive organizational environment. Technology and strategic decisions from top management are important, but they only work when combined with a good understanding of machining equipment and process conditions, a culture of continuous improvement, and shop floor communication [50].

For SMEs that aim to adopt circular practices, the behaviour of machine operators is crucial. Due to their often lean organizational structures, every worker, including machine operators, has a significant role in implementing and following company policies and recommended practices [49] . The actions of machine operators can directly impact material flows, waste reduction, and resource optimization, which are essential aspects of circularity.

In addition, SMEs frequently function within tightly interconnected supply chains or regionalized business ecosystems In situations like this, the dedication and knowledge of machine operators may have reverberating consequences, both internally and with external entities like as suppliers and rivals, toward the accomplishment of circular objectives which is line with Gulati [54] works regarding networking and knowledge diffusion. This is of the utmost importance since SMEs, which often have less resources at their disposal, are unable to bear the risks that come with deviating from circular processes. Not only can a well-informed machine tor who actively avoids cutting corners contribute to the reduction of waste [61], but they also assist ensure compliance with circular principles, which in turn enhances the transition of the SME toward a circular model. As a result, the role of machine operators is not only significant in the context of SMEs working toward circularity, but it is also absolutely essential.

Promoting a circular economy requires a holistic approach that considers human behavior and systemic factors, not only technology or operational improvements. This requires careful design, operation, and maintenance of systems, processes, and infrastructure that enable circular and sustainable behaviours and decisions. Human-technology interactions are complex, thus understanding them is imperative. The structure of systems can encourage or discourage sustainable behaviour [12]. The success of these systems depends on their operation and maintaining. For instance, a well-designed waste management system will fail without sorting methods and reliable maintenance. Implementing a circular economy requires an integrated approach that considers design, operation, and maintenance. This approach serves as a foundation for sustainable practices and fosters long-lasting collaborations. At the individual level, it entails nurturing adaptive skills, incentivizing sustainable behaviours, and creating a culture of knowledge sharing and accountability. Similarly, at the organizational scale, committed leadership, institutional learning, and customized performance metrics are key to promoting and maintaining circular practices.

6. Research Limitations and Suggestions for Future Research

This study provides valuable insights into how SMEs and cutting tool manufacturers can contribute to the principles of circular economy, specifically the 9Rs. However, some limitations need to be addressed in future research. Firstly, the study did not include resharpening companies and distributors, which leaves a gap in understanding the complete value chain. Secondly, the investigation focused only on SMEs and cutting tool manufacturers, which limits the generalizability of the findings.

To overcome these limitations, future research should expand the scope to include intermediary parties like resharpening companies. A more diverse and larger sample could also be used to investigate other industry-specific challenges and opportunities. Finally, future studies could consider the economic and operational feasibility of resharpening and recycling processes, providing a practical perspective to the 9Rs framework.

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