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Connecting Designers and Users: Lifecycle Collaboration for Circular Cutting Metal Tools

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Abstract: In this study, we delve into the circular transition facing metal cutting tools and bring attention to the challenges of collaboration throughout product lifecycles. Through a case study within metal cutting tools, we identify crucial obstacles to achieving circularity, such as the need for traceability, knowledge gap and optimal usage. To address these issues, we introduce a framework that promotes collaboration between designers and users, The framework utilized a dynamic QR to collect more data through the usage state of metal cutting tools to encourage circular practices through better management of product lifecycles. Our research indicates promising possibilities for promoting sustainability in metal tools through strategic design and sharing of information.

Keywords: Circular Economy, Traceability, Product-Service Systems, Lifecycle Collaboration

1 Introduction

In current times, there is a noticeable surge in economic development that has caused a shift in consumer behavior. The current market is marked by an influx of new products, which are introduced at an increasingly rapid pace, highlighting the decreasing lifespan of products (Thomé et al., 2016). This trend is fueled by the dynamic demands of customers, who are always seeking new and unique products, and the visible culture of conspicuous consumption, which perpetuates a cycle of buying and discardingThese factors are closely tied to the idea of circular progression and the goal of achieving net-zero waste (Zhidebekkyzy et al., 2022). They challenge the conventional linear economic models and call for a reassessment of sustainability practices and product innovation (Khalifa et al., 2022).

The current trajectory of rabid product launches contributes significantly to global emissions, with a substantial environmental footprint rooted in the manufacturing, distribution, and end-of-life treatment of consumer goods (foundation, 2019). The product development process has traditionally been a systematic approach designed to meet customer needs, encompassing stages from the initial gathering of requirements and evaluation of alternative solutions to the conceptualization and final delivery of the product. This process has been examined and refined over time as part of a broader sustainability agenda, incorporating concepts such as green design and eco-focus, supported by various tools and methodologies aimed at ensuring environmentally conscious production (De Jesus et al., 2021).

However, the ascendancy of the circular economy and its associated business models necessitates a recalibration of the product development process. As the notion of product value and customer ownership evolves, the imperative to align product design with the principles of circularity becomes increasingly pronounced. The shift from a linear 'make-use-dispose' model to a circular economy paradigm calls for a reimagined approach to product development that prioritizes resource efficiency, waste reduction, and the regenerative use of materials (Kirchherr et al., 2017; Kirchherr et al., 2023).

As part of circular economy paradigm, the concept of Product-Service Systems (PSS) has emerged as a business strategy to facilitate the circular economy transition, particularly through extending product lifecycles and promoting shared ownership in multi-owned products, sets the stage for this investigation. This paper explores the nexus between PSS design and enhanced collaboration within the circular economy, focusing on the metal-cutting tools industry. Through suggesting of digital-based information exchange and product traceability platform this paper argues that effective PSS design not only drives the circular economy by promoting sustainable consumer behaviours and resource efficiency but also increases and benefits from cross-sector collaboration. Through an in-depth case study in the metal-cutting industry, this research aims to uncover how PSS design principles can be optimized to enhance a collaborative environment that supports the circular transition.

2 Method

2.1 Data acquisition and Case study

The study focused on a collaborative buy-back program in the metal cutting tool industry. Stakeholders such as SMEs, a global manufacturer, and reshaping agencies were involved in the program. Each stakeholder played a crucial role in implementing circular economy practices. The SME users provided essential usage data, which was used to inform iterative design improvements through the stage-gate framework. Designers and engineers from the global manufacturer used this data to refine the tool designs, enhancing sustainability and circularity at each stage of development.

We collected data systematically through 12 semi-structured interviews with a varied group of individuals involved in the product lifecycle. This group included CNC machine operators, logistics officers, production planners, CEOs of SMEs, product specialists, and sustainability experts. These interviews provided valuable insights into operational challenges, sustainability practices, and the effectiveness of current recycling and refurbishing processes. In addition to the interviews, a workshop was held with representatives from four SMEs and tool manufacturers to explore avenues to enhance sustainable practices and to investigate specific issues faced by the buy-back program.

We analyzed the qualitative data using thematic analysis, which helped us identify and categorize themes related to each stage of the stage-gate process. This analysis allowed us to understand how different stages in the product development lifecycle could be optimized for better circularity. Key themes that emerged from the analysis included tool durability, ease of refurbishment, data tracking capabilities, and the environmental impact of tool disposal and recycling. These themes were aligned with specific stages in the stage-gate framework, ensuring that each phase of product development was informed by empirical data and targeted towards enhancing circular economy practices.

2.2 Stage gate design framework

The stage-gate framework, utilized in our methodology, orchestrates product development through a series of sequential phases (stages) interspersed with decision checkpoints (gates)(Cooper, 1990). This framework consists of sequential stages and decision checkpoints that effectively manage the product development process. By segmenting the journey into manageable phases, we can closely monitor and evaluate progress at each stage. These stages, which include concept development, design, testing, and launch and post-launch, offer a systematic approach to ensure high-quality results. At each gate, the project's advancement is evaluated against predetermined standards, only allowing those that meet the necessary requirements to move forward (Cooper, 2008). It was the intention in our research to choose the stage-gate methodology because it has an orderly progression that improves risk management and enables optimisation of resource distribution. We selected the stage-gate model because it is often seen as a foundation item for many product design frameworks because of its simplicity and structured approach to application; the stage gate model allows for an extensive exploration of all possible areas in which a designer could make his/her input during the development of a product. in analysis phase, the information collected from the usage phase of the cutting tools is linked to different phases in the stage gate framework where they support designers’ pro-circular actions.

3 Theoretical framework

3.1 Product Services Systems Design

PSS represent a transformative business model that integrates products and services to meet customer needs more sustainably and efficiently. This paradigm shift, as outlined by Tukker and Tischner (2017) emerges in response to the increasing complexity of products and the dynamic nature of customer requirements, necessitating innovative approaches that go beyond traditional product-centric models. PSS encompasses various forms, including use-oriented, result-oriented, and product-oriented services, each designed to extend product lifecycles, reduce environmental impact, and improve customer satisfaction (Baines et al., 2009; Tukker, 2004)

The transition to PSS presents challenges that require a nuanced understanding and strategic approach to overcome. Central to these challenges is the cultural and behavioural resistance encountered in shifting from a traditional product ownership model to service-oriented consumption patterns. This resistance necessitates a concerted effort in consumer education and the development of incentives to encourage behavioural change, as highlighted by Tukker (2004) . Compounding the complexity are the economic and financial viability concerns of PSS, where the unpredictability of revenue streams and higher upfront costs demand innovative financing and business models to ensure profitability (Baines et al., 2009). Moreover, the absence of supportive regulatory frameworks and policies further hinders PSS development, underscoring the need for government intervention to foster an enabling environment through incentives, regulations, and standards (Mont, 2002). Operationalizing PSS also presents technological and logistical challenges, especially for SMEs, requiring advancements in tracking, maintenance, and lifecycle management technologies, alongside efficient supply chain operations (Vezzoli et al., 2015). The complexity of integration and coordination across different stages of the value chain necessitates robust collaboration among stakeholders, presenting challenges in partnership management, interest alignment, and the seamless delivery of integrated solutions) (Tukker and Tischner, 2017). Furthermore, designing for PSS demands a paradigm shift towards systems thinking, requiring new design philosophies that incorporate not only the product but also the associated services and their interactions over the product lifecycle (Manzini and Vezzoli, 2003). Addressing these challenges is critical for the successful implementation of PSS, which holds significant potential for sustainability transitions. However, recent researches suggest that integration of AI and digitalization in PSS brings about remarkable improvements in operational efficiency, personalized customer experiences, and ecological sustainability.

With AI, there is the ability to forecast and tailor services, leading to efficient resource utilization and reduced environmental harm. Moreover, digital tools allow for real-time monitoring and data analysis, enhancing product lifecycle management and fostering stronger customer engagement (Ghoreishi and Happonen, 2020; Li et al., 2020; Manser Payne et al., 2021).

3.2 The role of Product design in PSS

In the evolving landscape of PSS, the role of product designers transcends traditional design paradigms, positioning them as key agents of systemic innovation and sustainability. As highlighted by Mont (2002), systemic design thinking enables product designers to address complex sustainability challenges by integrating products and services into cohesive solutions that meet holistic user needs. This approach is underscored by Tukker (2004), who emphasizes the importance of designers in embedding sustainability into the PSS lifecycle, advocating for designs that facilitate longevity, reuse, and recycling. Furthermore, Baines et al. (2009) articulate the significance of user-centred design in PSS, where designers must delve deeply into understanding user experiences to ensure the seamless integration of products and services. The collaborative design process, as noted by Manzini and Vezzoli (2003), requires designers to work across disciplinary boundaries, leveraging their unique ability to visualize and communicate complex concepts. This multidisciplinary collaboration is critical in fostering innovation and adaptability in PSS offerings. Moreover, the adaptation of design methodologies to suit the intricacies of PSS is a critical contribution of product designers, highlighting their role in pioneering new approaches that cater to the specific demands of integrated product and service models (Mont, 2002; Tukker, 2004). This emphasizes the critical significance of product designers in spearheading the movement towards sustainable and user-oriented PSS, signifying a notable change in the philosophy and execution of design towards more sustainable product design practices.

3.3. Metal cutting industry and sustainability challenges

According to the European Commission (2023); The metal-cutting industry plays a crucial role in the worldwide manufacturing sphere, but it faces major hurdles due to its reliance on scarce metals like tungsten, titanium and cobalt. These valuable resources are essential for creating cutting tools and are classified as Critical Raw Materials (CRMs) due to their economic value and the potential consequences of supply disruptions. This dependence highlights the industry's vulnerability to fluctuations in material availability and calls attention to the environmental impact of mining and processing these metals (Cimprich et al., 2022). This highlights the industry's vulnerability to fluctuations in material availability and brings to light the environmental repercussions of metal extraction and processing. A circular economy approach offers a promising solution to these sustainability issues by promoting resource efficiency, reducing waste, and prolonging product lifespan through recycling, remanufacturing, and reuse. In this sector, the recycling of critical raw materials from end-of-life tools and the implementation of advanced manufacturing techniques for improved tool durability emerge as crucial sustainable methods (Kumar et al., 2023; Rizzo et al., 2020). These efforts not only reduce the environmental impact of raw material extraction and processing but also pave the way for increased sustainability in the industry.. These measures not only diminish the environmental footprint associated with raw material extraction and processing but also contribute to stabilizing the supply of these critical materials(Cimprich et al., 2022).

However, the integration of circular economy principles in the metal cutting industry encounters substantial barriers, such as the complexity of ensuring high material efficiency in environments characterized by multi-product ownership and diverse tool lifecycles (Kumar et al., 2023; Pervaiz et al., 2020). The successful implementation of circular strategies necessitates a holistic approach, including the design of tools for enhanced durability and recyclability, the advancement of recycling technologies, and the creation of closed-loop supply chains. Moreover, the industry's shift towards sustainability is impeded by challenges in technological innovation, economic feasibility, and the need for regulatory frameworks that support sustainable practices. Addressing these challenges requires a concerted effort from stakeholders, significant investments in research and development, and the advocacy for policies that facilitate sustainable practices (Gunasekara et al., 2023; Saari et al., 2021).

3.4. Digital product passports in the context of metal cutting tools

Digital product passports (DPPs) are becoming increasingly important for supporting circular economy efforts by providing traceability and transparency throughout a product's lifecycle. They help stakeholders make better decisions by giving them access to detailed product information, such as where raw material source, usage and recycling, maintenance remanufacture or disposal instructions. This data is essential for meeting regulations and promoting sustainability as DPPs seek to streamline the diverse systems in place in the EU and other regions, improving the usefulness of these passports across various sectors (Jansen et al., 2022; Jensen et al., 2023). However, a major drawback of the current DPPS is its limited flow of information. The system mainly relies on data inputs from suppliers and product designers, which might not fully capture the whole lifecycle of the product. This omission can lead to a lack of integration of user feedback, which is essential for extending the product's lifespan and enhancing overall circularity (Korhonen et al., 2018). To address this, it is recommended that DPPS should incorporate mechanisms that allow for feedback loops. These loops could enable users to contribute to data on product usage and end-of-life outcomes, thus enriching the passport's usefulness and ensuring a more dynamic, responsive system that aligns with the principles of the circular economy. However, Metal cutting operations involve harsh operating conditions, including high temperatures, vibration, and constant contact with hard materials. As a result, the wear and tear on tools such as inserts and drills is significant (Rizzo et al., 2020). Embedding DPPs into these small-sized tools is difficult, and maintaining the integrity and readability of the digital data over time is a significant challenge. Traditional DPP integration techniques, which may work for larger tools, are impractical due to the small size of these tools. Therefore, innovative approaches are necessary to ensure that these passports can withstand operational rigours and continue to provide valuable lifecycle data.

4. Case study from metal cutting industry

This case study explores a collaborative buy-back program within the metal cutting tool industry that illustrates a functioning circular economy model. The program involves the reuse and recycling of metal cutting tools, facilitated by interactions between SMEs as tool users and a global tool manufacturer. The lifecycle begins with SMEs using newly manufactured cutting tools for various metal cutting operations. As these tools begin to wear, SMEs perform in-house maintenance and resharpening to extend their usability, ensuring tools are kept in optimal condition with minimal downtime. Tools that cannot be properly maintained in an on-site setting are sent back to the manufacturer so that they can go through a comprehensive evaluation process. It is after the manufacturer has assessed them that s/he determines if they can still serve any other purpose or they should simply be recycled where the raw materials will be extracted to be used in produce new cutting tools. These tools are then adjusted according to quality specifications so as to fit perfectly into the manufacturer's system if they are found proper. In this setup, SMEs participate not only in the initial usage but also in the ongoing maintenance of the tools, while the manufacturer plays a crucial role in the advanced refurbishment and recycling stages. This self-contained approach to tool management underscores the collaborative efforts between users and providers to maintain tool functionality and sustainability throughout their lifecycle, enhancing the operational efficiency and environmental integrity of the industry (See Figure 1).

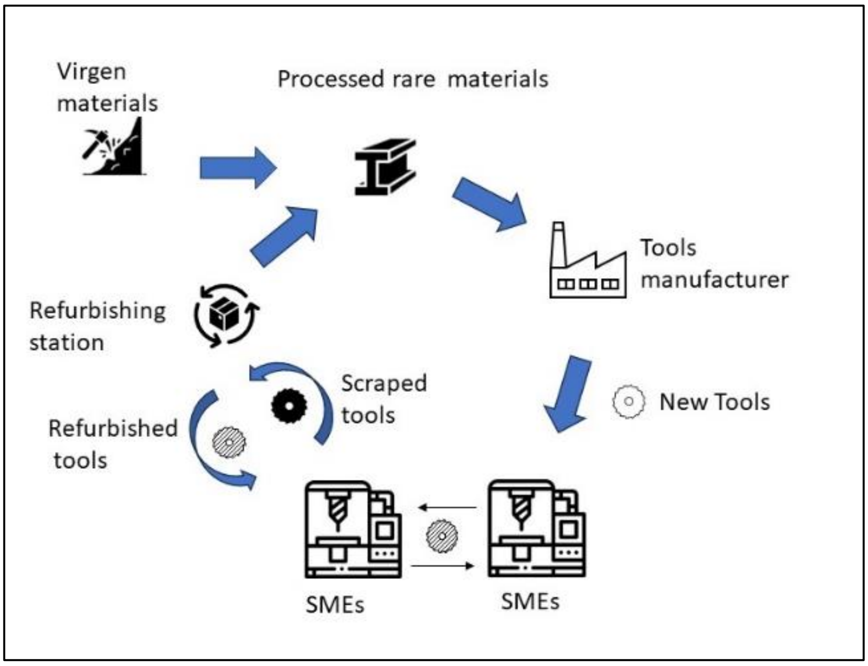

Figure 1. Metal cutting tools life cycle in buy-back program

5. Findings

5.1 Circular transition design considerations

The shift towards a circular economy is a transformative approach aimed at redefining traditional consumption and production towards sustainability. The model suggested by Wasserbaur et al(2022) is well established model that describe the transition towards circular economy and it will be used in this paper .It hinges on designing products for greater durability and recyclability, alongside innovating circular business models that prioritize service over product ownership.

This includes encouraging practices such as leasing, sharing, and product-as-a-service to extend the lifecycle of resources. Key to this transition is also the establishment of reverse supply chains to recover and repurpose end-of-life products. Supporting these initiatives are necessary enabling conditions like progressive policies, dedicated infrastructure, and consumer engagement strategies. Collectively, these efforts strive to minimize waste and environmental impact, fostering a regenerative economic model that efficiently utilizes resources while promoting ecological balance.

The product development process within the circular economy paradigm necessitates a comprehensive and systematic approach, focusing on the integration of design and business strategies to facilitate the transition from linear to circular models (Chen, 2022). Central to this is the adoption of product design strategies that emphasize durability, reparability, and adaptability, aligning with the principles of slowing, closing, and narrowing resource loops to enhance resource efficiency and minimise waste (Jaeger and Upadhyay, 2020). From a technical perspective, this involves designing products with extended lifespans, modular components for easy repair and upgrade, and materials that can be effectively recycled or biodegraded, thereby supporting the circular flow of resources (Chatty et al., 2022).

When it comes to achieving a circular economy, businesses must embrace new and creative models that prioritize access rather than ownership. Through approaches like product as a service (PaaS) and industrial symbiosis, material recovery can be maximized. These innovative models not only aim to prolong the lifespan of products and components, but also challenge companies to rethink their value proposition to consumers. This means placing a greater emphasis on sustainable use and efficient resource management throughout the entire product lifecycle.(Esenduran and Kemahlıoğlu‐Ziya, 2015; Pieroni et al., 2019). The success of achieving a circular economy rests on the symbiotic relationship between technical and business considerations. It is imperative for companies to seamlessly incorporate circular design principles into their business models and incentivize sustainable consumption patterns. This requires a shift in corporate culture and consumer behavior, supported by progressive policies and technological advancements to cultivate an environment conducive for the circular economy to flourish (Chu and Wever, 2022).

5.2 Challenges for circular transition

The workshop and interview revealed several challenges hindering the collaboration towards implementing circular economy strategies between manufacturers of metal cutting tools and SMEs users. These challenges can be summarized and categorized as follows:

- Traceability Issues: Tracking the usage and condition of cutting tools across various models, especially due to their small sizes and tendency to wear rapidly, proves to be a major hurdle in creating a cohesive traceability system. The absence of universal techniques for monitoring tools on a larger scale further complicates traceability efforts, making it difficult to effectively implement circular strategies.
- Human Judgment Variability: The integration of circular practices into operational procedures is complicated by the subjective nature of human judgment when monitoring tool condition. This introduces a level of complexity, as operators' competence and subjective judgment can result in premature tool replacement, as well as potentially unorganized work structure and an overall lack of efficiency in sustainable procedures..
- Operational Inefficiencies: These stem from the rapid replacement practice and lack of refurbishing practices, which not only lead to increased waste but also oversee the potential for extending tool life through circular practices such as repair, refurbish, and remanufacture.
- Waste Management and Recycling Challenges: Recycling poses a considerable challenge, especially for items crafted from precious metals or coated with specialized materials. These particular tools often face obstacles when it comes to the recycling process. Their low concentrations or intricate compositions make it difficult for current methods to effectively recover them.
- Knowledge Gaps: Many stakeholders are not fully aware of the advantages and feasibility of implementing circular tools and methods. This void blocks the incorporation of circular behaviors and technologies.

6. Discussions

6.1 Suggested traceability concept

The solution posited in this study represents a transformative framework that seeks to augment the role of the product designer in advancing circularity within the lifecycle of metal cutting tools. This framework pivots on the integration of a product-as-a-service (PaaS) model, facilitating a continuous flow of information between the product designers and the users (see Figure 2).

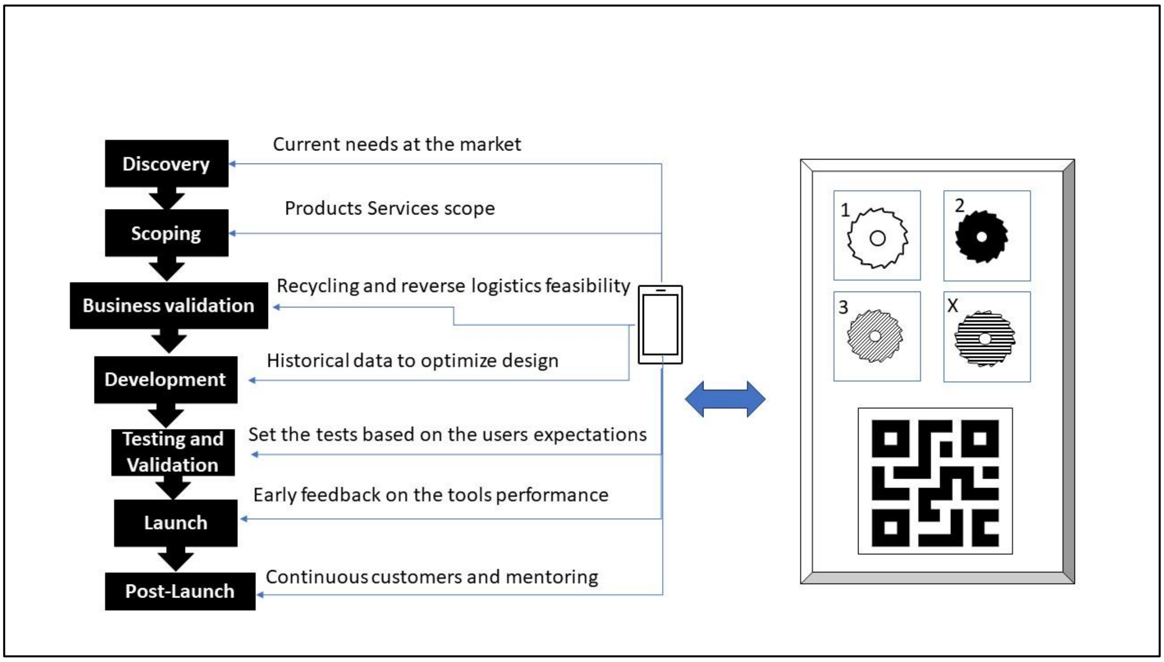

Figure 2. Suggested traceability digital framework and exchanging information with designers in product development stage-gates model

Given the small size and diverse dimensions of metal cutting tools, the proposed system introduces a three-digit identification code inscribed on each tool, which is then allocated to a designated compartment within a small box. This box features a QR code that interfaces with a server underpinning the shared PaaS platform. When an operator scans the QR code, they can register a new tool within the box's compartment, recording the tool's three-digit code into the system. Subsequent to each use, the operator logs the tool's utilisation time, aligned with the process design specifications provided by the production engineer. Over time, the manufacturing company or production engineer can use the collected data to predict how much longer the tool will last. Furthermore, after each scan, the company can provide customized instructions to optimize the tool's usage and performance. As the tool approches the anticipated time for cutting quality decline, the shared platform forwards precise reconditioning instructions. Post-reconditioning, this data enriches the tool's historical record, thereby not merely serving as a digital passport of the product but as a dynamic record book of its service history. This innovative strategy goes beyond the conventional methods of product identification by promoting a continuous value proposition, sharing specialized expertise, and providing personalized educational materials for end users as companies and operators or remanufacturing companies. Simultaneously, this traceability platform provides designers with invaluable, real-time insights throughout the entire product-service cycle. By leveraging these insights, designers can improve the product development process, informed by empirical user data and usage metrics. This model represents the transition towards a circular economy, emphasizing the significance of sustainability and maximizing resource efficiency. Moreover, in the context our proposed digital platform and QR code tracking system, several types of operational data are collected and managed. These include QR code scans that record tool usage times, condition assessments, and refurbishment cycles. This operational data is crucial for maintaining a continuous feedback loop between tool users and designers, fostering the development of more sustainable tool designs. All data is securely stored on encrypted cloud-based servers to ensure data integrity and protect against unauthorized access. A structured query system facilitates efficient retrieval of specific operational metrics, such as usage frequency and maintenance intervals, which are essential for real-time analysis and decision-making. To safeguard this information, we implement advanced encryption and adhere to strict access controls, ensuring that only authorized personnel can access or modify the data, thereby maintaining compliance with stringent data protection standards.

6.2 Enhancing Circular Economy through Collaborative SSP Design

The framework proposed offers a fresh perspective on PSS design, promoting a more collaborative and efficient process that aligns with the goals of a circular economy. By facilitating a constant exchange of information between designers and end-users, this framework excels in its ability to refine products and enhance services from a circular economy standpoint. By implementing a unique identification system for each tool and integrating it with a digital interface at the tools books, designers gain rapid and accurate insights into how their products are being utilized and how well they are performing. This immediate access to feedback is crucial in recognizing usage patterns, identifying design areas for enhancement, and tailoring maintenance schedules to prolong the lifespan of the product. These are all fundamental principles of the circular economy. Moreover, by implementing a QR-coded system that is connected to a shared platform, it truly embodies the principles of collaborative circular design. This allows for multiple parties, including operators and production engineers, to actively participate in and benefit from a centralized pool of knowledge. Not only does this raise streamlined tool usage, but it also aligns with the objectives of the PaaS model, which focuses on providing value through services like maintenance, repair, and operational efficiency, rather than solely relying on product sales. The framework transcends conventional PaaS design by embedding within it a mechanism for continuous learning and adaptation. Thus, it guarantees that the product-service offering develops according to user input and environmental factors, ultimately promoting a flexible and adaptive approach to PSS design that aligns seamlessly with the principles of the circular economy. As a result, the final product not only prioritizes sustainability, but also contributes to the important shift from ownership-based consumption to usage-based consumption, a core belief of those championing the circular economy movement. In addition to its other benefits, this framework effectively tackles a major issue often associated with implementing circular economy strategies: the possibility of decreased sales of new products as a result of longer product lifecycles. By actively encouraging the creation of innovative services and product improvements that cater to consumers' specific needs, companies can effectively offset any potential decrease in revenue from product sales. Essentially, this framework leverages collaborative inputs to create a PSS design that is inherently circular, resilient, and responsive to the lifecycle realities of metal cutting tools, ensuring that both product integrity and service excellence are maintained throughout the tool’s lifespan.

6.3 Understanding design requirements for Paas System

The suggested model can act as a supporting tool in the new PaaS designing process where designers flow their product and work closely with stakeholders throughout the product life cycle and designing phases. incorporating a product-service system into the stage-gate design process introduces a dynamic method for improving the circularity of metal cutting tools. In the preliminary *Discovery phase*, the utilization of live data aids in the development of tools that prioritize recyclability and effective maintenance including understanding the current needs in the market and possible opportunities. As we move into the Scoping stage, this data plays a crucial role in shaping the framework for optimizing tool usage, guaranteeing that the design is optimized for peak performance and productivity, this is the stage where supporting services like training and reverse logistics can be identified . As the process advances to *Business Validation*, insights into tool condition and lifecycle feed into the economic feasibility of the design and associated services costs , supporting a business model that prioritizes sustainability. In the *Development phase*, the insights gathered are pivotal in refining the design for ease of maintenance and recycling, with considerations for material selection and product architecture that facilitate these processes. During the *Testing and Validation stage*, the tools are carefully evaluated using usage data to ensure they meet the necessary standards of durability and maintainability. This is vital in extending the lifespan of the product. Once the product is launched, users are informed about its effectiveness in terms of recycling and maintenance, highlighting the tool's role in promoting a circular economy. Furthermore, users are also provided with training to help them optimize their usage of the tool. This emphasizes the importance of sustainable practices in the overall product design. During the *Post-Launch* phase, designers gather ongoing feedback from the shared platform to evaluate how the tool is meeting circular economy benchmarks. This stage is crucial for making iterative improvements, identifying any areas needing improvement, such as recycling processes, monitoring the tool's condition, and measuring the effectiveness of user training.

7. Conclusion and Limitations

Through this articles, we highlight the importance of establishing seamless communication channels between designers and users of product-as-a-service (PaaS) systems, specifically in the metal cutting tools industry. Creating strong feedback loops is crucial for improving tool design and promoting sustainability. However, some obstacles need to be overcome to implement such systems, such as the security risks associated with data sharing, and the need for robust IT infrastructure to support real-time data transmission and processing. Furthermore, integrating new processes into existing workflows may require longer setup times and temporarily reduce efficiency. Future studies should focus on finding ways to overcome these challenges while enhancing the practicality of integrating PaaS systems in industrial settings.

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