Article

Embedding Product-Service System of Cutting Tools into the Machining Process: An Eco-Efficiency Approach toward Sustainable Development

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Abstract: Product-Service System (PSS) is a sustainable strategy that shifts the focus of the business from selling physical products to providing service by using the product. The innovation proposed in the PSS, focused on sustainable production and consumption, is consistent with the sustainable development goals of the United Nations 2030 Agenda. The scientific literature on PSS in machining showed studies that address the economic factor of PSS contract, machine maintenance and logistics and operational process improvement. Then, there is a lack of studies on the assessment of the PSS in machining under a sustainability factors perspective. Thus, the objective of this paper was to evaluate the economic, environmental, and social advantages of PSS cutting tools in machining. Consistent with this aim, the research focused on a case study in a diesel engine parts machining company. From an economic point of view, the results indicated a reduction in operating costs of US\$ 1,206,080 per year, which allowed a nine-month return on investment. From an ecological perspective, the recovery of 602 kg of carbide per year mitigated the environmental impact of tungsten and cobalt exploration. These results are even more expressive because it deals with scarce metals. Furthermore, technological advances reduced the risk of injury to operators. This research increased knowledge on PSS in machining by presenting an original study that led the analysis under a sustainability perspective. Moreover, this study contributes to managers by showing the business model's advantages that reduce operating costs and socio-environmental impacts, enhancing sustainable development.

Keywords: product-service system; cleaner production; sustainable development; cutting tool; machining

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1. Introduction

Product-Service System (PSS) has been adopted in several business sectors that seek to develop sustainable business models, based on consumption and production, which support the transition towards cleaner production and circular economy [1]. PSS is a sustainable strategy that shifts the focus of the business from selling physical products to providing service for product use, which are more eco-efficient in terms of resource optimization [2]. PSS contractors can reduce costs and increase productivity through value-added services [3]. PSS providers are required to add more value to the products they offer and augment and diversify the services related to these products [4]. While PSS, on the one hand, strengthens the link between supplier and customer, which contributes to improving competitiveness, on the other hand, the personalized product service makes it difficult to replace supplier [5]. Nevertheless, in most cases, PSS has shown sustainable benefits that offer win-win relationship to service providers and customers [6,7].

The search for studies in the literature on PSS in machining identified articles that addressed this theme. Four studies address the economic factor of PSS contracts in machining. A framework for quantifying the uncertainties in the cost-benefit estimation of machine tool PSS contracts was provided in [8]. Zhang et al. [9] developed a method based on Pareto principles to evaluate the economic viability of PSS CNC machines. Similarly, a cutting tool condition monitoring model to increase the quality and profit of PSS cutting tools and a PSS cost estimation scheme of cutting tools have been introduced in [6] and [3], respectively.

Four other studies addressed PSS in machine maintenance. In 2021, Chang et al. [10] provided a framework for maintenance decision-making oriented on CNC machine services. Wang et al. adopted an active preventive maintenance approach of PSS-based CNC machines [1]. A model that integrates the PSS of machining machinery maintenance was developed by considering the availability of repair and machine parts [11]. Similarly, Wang et al. [12] introduced a collaborative maintenance planning system integrated into the machine tool PSS model.

Two studies developed PSS models focused on logistics and operational process improvement. A cutting tool PSS model based on demand prediction and just-in-time tool delivery [13] and a PSS framework of CNC machines, hardware, and software was introduced based on availability and machining capability improvement [14].

Although the approach of PSS in machining was detailed in the mentioned research, there isn't a study that evaluated the economic, environmental, and social gains of PSS in machining. The previous papers focus on the economic aspect, while the environmental and social factors were neglected in the studies about PSS in machining. The research gap identified in the literature suggested the following question: the PSS in machining can be an eco-efficient alternative for sustainable development in the industry? To provide an answer to the question raised, this research aims to evaluate the economic, environmental and social advantages of PSS cutting tools in machining.

These benefits, achieved through the modernization of production processes, led to an increase of the eco-efficiency adopting a strategy consistent with sustainable development goals, #9 (Industry, innovation and infrastructure) and #12 (sustainable production and consumption), defined in the 2030 Agenda prepared by the United Nations Organization [15]. The process modernization is consistent with the concept of cleaner production, which contributes to increasing the competitiveness of companies through the reduction of cost and environmental impact [16–19]. In this perspective, suppliers adopting the environmental practices allow supporting the companies in the business to achieve sustainable development goals [20]. Economic growth, ecosystem conservation and human welfare are the basis to achieve sustainability objectives [21,22]. However, there is no clear evidence of the effects of PSS in the industry on sustainability performance [23]. These facts enhance the contribution of a study that measures the benefits of PSS cutting tools in machining under a sustainability perspective.

This research adopted the case study methodology with a quantitative approach to evaluate the benefits of PSS in a diesel engine parts machining company. This is an innovative approach that embedded the sustainability factors into the assessment of PSS cutting tool in machining process of engine parts. The diesel engine has several applications such as power generators, automotive, tractors, and marine [24]. The advantages of diesel engine generators have increased considerably for different reasons such as high level of reliability, high speed at performance as well as easy implementation in the isolated hybrid microgrids [25]. The diesel engine is being further developed to compete with other power sources as the engine is advantageous regarding logistics, storage, efficiency and compactness [26].

The economic assessment consisted of payback analysis based on operational costs and investment of PSS implementation. In terms of the environmental factor, the mass balance of recycling cutting tools at the end of service life. Cutting tools are produced adopting scraps of raw materials such as tungsten and cobalt. The tungsten carbide endows

the alloy an excellent hardness and superior wear resistance [27]. The excellent cutting and wear resistance properties of its carbides have made it a strategic commodity of high importance globally, highly employed in the manufacturing, petrochemical, construction, gas drilling and mining sectors [28]. These elements are fundamental to promoting global industrial and technological development [29]. There is a real risk due to metal scarcity and to the impact of exploration of these metals involving geopolitical risk and human rights abuse [29]. Therefore, recycling and the technical loops are strategies to ensure resource availability over time [30]. The social factor analysis considered the improvements to reduce the ergonomic risks.

The motivation of this research is to offer a work not yet developed in the literature on the economic, environmental, and social advantages of PSS in machining. In addition, this study intends to encourage industrial managers to seek PSS businesses that increase the eco-efficiency of their production processes, such as cleaner production practices towards sustainable development. Top management should increase creative process engagement among employees as it is a crucial intangible resource for green process [31].

This article is structured as follows: The systematic review of the literature is presented in Section 2, in which the PSS in machining is explored in depth. The research methodology is shown in Section 3. The economic, environmental and social evaluations of PSS in an engine parts machining industry are conducted in Section 4. The discussions of the case study results and the findings of the theoretical basis are shown in Section 5. Finally, Section 6 highlights the conclusions, contributions of the work, limitations, and future research suggestions.

2. Literature Review

The systematic literature review identified a sample of 10 articles on PSS in machining. The scope of the search and the selection criteria used are presented in the methodology section. The approach adopted in selected papers is related to PSS economic analysis, CNC machine maintenance, and logistical and operational process improvement.

The studies focused on the economic aspects, evaluated the PSS contracts' economic feasibility, cost-benefit, and uncertainties. In this context, Farsi and Erkoyuncu [8] presented a framework to quantify machine tool PSS contracts' uncertainties under an economic perspective. The model estimates the machine's service life cost, including the PSS contracts based on service level and on spare parts availability. Several parameters were considered in the analysis of cost-benefit uncertainty, such as machine acquisition price, rental/leasing, assembly, and disassembly of the machine in the customer, installation, testing, maintenance and retrofit. The results highlighted that the PSS is advantageous in long-term contracts. Zhang et al. [9] developed a method based on Pareto principles to evaluate the economic viability of PSS of CNC machines. The CNC machine has been deployed in the physical and service modules.

The first includes body, tool holder, spindle, tailstock, hydraulic and electrical parts. The second module includes human-computer interaction, debugging service, machine maintenance, installation, emergency rescue, remote service, test, and quality assurance. Both modules' integrated analysis allowed the engineers to identify the customer needs and deliver the best deal. Zhang and Sun [6] have developed a cutting tool condition monitoring model to increase the PSS quality and the profitability in this business. Despite the positive expectation about monitoring cutting tool conditions, improvements to the Tool Condition Monitoring (TCM) system have been identified. The quality of service depends on the accuracy, reliability and robustness of the functions of the TCM system, which are very limited. Moreover, it was highlighted the unavailability of the cutting tool services in real-time due to the complexity of the TCM system. In this regard, the integration of the Internet of Things (IoT) and a cloud manufacturing service system could substantially improve the performance of the TCM system. Mu et al. [3] developed a method of estimating the PSS cost of cutting tools, oriented on activity-based costing. The activities raised by the study were machining, management, maintenance and repair

operations. The pricing parameters of the service include time-consumed tools and labour costs. Machining and repair activities were associated with tool consumption, while management and maintenance to labour costs.

Chang et al. [10] developed a framework for decision making in the maintenance of CNC machine services based on a distributed blockchain network. Implementing a collaborative sharing environment allowed to improve the diagnose failures and manage PSS resources for CNC machine maintenance. In this framework, stakeholders' involvement from different organizations allows broadening the knowledge to implement proactive performance-based maintenance PSS planning. Similarly, Wang et al. presented a PSS approach to preventive maintenance of CNC machines adopting Industry 4.0 technologies. CNC machines were distributed to customers, and a service provider monitored their activities. A neural network was trained to predict the rest of the service life of the main machine components, which increased the accuracy of prediction, improved preventive maintenance planning, and reduced costs and resource consumption [1]. A model to link a combination of CNC honing machines with similar functions in a service network [11]. The network analyzes the machine availability identifying failures and critical nodes, with the aim to optimize the execution of maintenance services. Wan et al. [12] investigated the relationships between different stakeholders in the life cycle of machine tools to develop a collaborative machine tool maintenance planning system. The sharing of production planning information and machine conditions between users and machine tool manufacturers allowed to schedule a maintenance planning optimizing the number of parts to repair and replace, ensuring a high service level and low operation costs.

The PSS model of cutting tool proposed by Sun et al. [13] was oriented to predict demand and just-in-time delivery of tools. The research jointly analyzes three aspects: the cutting tool selection, the demand prediction, and the cutting tool delivery. The results showed that outsourcing management of cutting tools reduces costs and improves productivity. Zhu et al. [14] presented a PSS framework of CNC machines, hardware, and software, based on machining capability and continuous improvement. The framework introduced changes the role of machine tool vendors to machining capability suppliers, involving machine operation, repair, and maintenance. The innovative business, not yet familiar to companies of this segment, combined with the lack of protection of technological intellectual property, were barriers to the implementation of PSS proposed by the study.

The main information of the collected articles are described in Table 1.

Table 1. Articles identified in the systematic literature review on PSS in machining.

Authors	Year	Title	Journal	Country	Methodology	PSS Approach
Chang et al.	2021	A maintenance decision-making oriented collaborative cross-organization knowledge sharing blockchain network for complex multi-component systems.	Journal of Cleaner Production	China	Case study	Maintenance
Farsi and Erkoyuncu	2021	An agent-based approach to quantify the uncertainty in product-service system contract decisions: a case study in the machine tool industry.	Int. J. Production Economics	UK	Case study	Economic analysis
Wang et al.	2020	An active preventive maintenance approach of complex equipment based on a novel product-service system operation mode.	Journal of Cleaner Production	China	Case study	Maintenance

Table 1. Cont.

Authors	Year	Title	Journal	Country	Methodology	PSS Approach
Zhang et al.	2019	Extraction of association rules in the schematic design of product service system based on Pareto-MODGDFA.	Computers & Industrial Engineering	China	Case study	Economic analysis
Chang et al.	2018	A function availability-based integrated product-service network model for high-end manufacturing equipment.	Computers & Industrial Engineering	China	Case study	Maintenance
Zhang and Sun	2018	Enabling a cutting tool iPSS based on tool condition monitoring.	Int. J. Adv. Manuf. Tech.	China	Experiment	Economic analysis
Wan et al.	2017	Process and knowledge management in a collaborative maintenance planning system for high value machine tools.	Computers in Industry	China	Case study	Maintenance
Sun et al.	2016	Cutting-tool delivery method in the context of industrial product service systems.	Conc. Eng. Research & Applic.	China	Case study	Process improvement
Mu et al.	2012	Machining process level cost estimation in cutting-tool IPSS.	Applied Mech. and Materials	China	Case study	Economic analysis
Zhu et al.	2011	Implementing an industrial product-service system for CNC machine tool.	Int. J. Adv. Manuf. Tech.	China	Experiment	Process improvement

The search in the databases considers the publication' year as an open field. Therefore, the evidence that the selected articles have been published in the last 10 years denotes the PSS in machining as a contemporary theme. The little amount of research on PSS in machining showed the opportunity to investigate this research area. The environmental and social factors are two aspects outside the PSS analysis conducted in the published studies. This lack highlights the contribution of this research including the sustainability factors in PSS analysis in machining.

3. Materials and Methods

The data analyses conducted adopts a quantitative and qualitative approach. The case study facilitated the understanding of the subject in practice to favour the critical analysis of the background theory [32].

The planning and execution of the case study followed the five steps defined by Yin [33]: (i) problem definition; (ii) research delineation; (iii) data collection; (iv) data analysis; (v) results. The first step in a case study consists of defining the research problem. The second stage refers to the methods adopted to carry out the case study and identify the aspects out of the research scope. The third stage consists of collecting the data that occurred in this study through semi-structured interviews, observation of the production process and management reports. The fourth stage is data analysis, in which economic, environmental and social evaluations were carried out. The fifth step suggests the analysis of the results, which in this research led to checking if the PSS in machining is an eco-efficient alternative for sustainable development in the industry.

The definition of the research problem was performed through a bibliometric and systematic literature review. A bibliometric survey quantifies the scientific literature on a specific topic [34], through which it is possible to identify empirical data that can be displayed in predefined selection settings [35]. The results of the bibliometric research can be systematically reproduced [36]. Therefore, the compilation of relevant information on a given subject becomes strategic for future studies related to the topic researched [37]. Di

Vaio et al. [38] recommend four steps to guarantee a reliable systematic literature review that involves: (1) extraction of articles from databases, (2) identification of relevant articles, (3) manual localization of highly cited articles and (4) identification of other influential articles. With this, the bibliometric and systematic literature review ensured that the studies included in the research theme had been selected. The literature's research aimed to identify articles related to PSS, cleaner production, and machining in the present work. Bardin [39] recommends seeking papers using keywords, analyzing the found articles and choosing those that are relevant to the study. For this scope, a set of keywords was defined to identify documents in the scientific databases: Scopus, ScienceDirect, Web of Science and Wiley. The search has been conducted based on preliminary information collected through Scopus, which is the largest database with multidisciplinary scientific literature analysis tools [40]. The Science Direct, Web of Science and Wiley electronic databases were also selected due to their relevance to the theme and research field [41]. The keywords were combined into pairs, as shown in Table 2.

Table 2. Keywords used in the search engine and the number of articles.

Keywords Combination	Scopus	ScienceDirect	Web of Science	Wiley
"Product-service system" or "PSS" and "cleaner production"	14	8	1	0
"Product-service system" or "PSS" and "machining"	23	15	0	0
"Product-service system" or "PSS" and "cutting tool"	7	0	0	0

The search of the databases was carried out in August 2021. All documents non-refereed as scientific documents (journal articles), such as conferences, books, and magazines, were excluded from the initial search in the scientific database [42,43]. The total number of documents that combined the terms shown in Table 2 in the title was 68 articles. A spreadsheet was used to record the main information of the selected documents. The next step was to remove duplicate documents; 11 repeated articles were identified. The list of 57 papers is presented in Appendix A. The number of papers by year of publication is shown in Figure 1.

Figure 1. Number of papers by year of publication.

The content analysis followed the procedure of Del Giudice et al. [44] that recommends each author proceed initially with the content analysis by reading the abstracts and, after that, the entire document analysis for papers related to the research objectives. The analysis

of the remaining 57 studies revealed that 47 studies addressed PSS in other areas such as household appliances [45], construction [46], truck maintenance [47], tourism [48], food and beverage sales machines [49], waste management [50] and aircraft [51]. Thus, the selection of scientific papers identified 10 articles on PSS in machining. According to the Preferred Reporting Items for Systematic reviews and Meta-Analyses (PRISMA) method [35], the selection criteria used in the search for articles were summarized in Figure 2.

Figure 2. Stages of selection of articles in the literature. Source: Adapted from Moher et al. [35].

The analysis of the 10 articles allowed to consolidate the theoretical foundation of this study that supported the field research carried out in a process of machining diesel engine parts. Data collection was conducted by observing the production process, analyzing documents and interviewing technicians and managers of the companies involved in the PSS contractor.

The collected data allowed evaluating the advantages due to PSS implementation. The PSS implementation required a previous period to monitor and analyze the machining process in special cutting tool conditions to establish the monetary values of the business agreement. The cutting tool condition monitoring was performed by Zhang and Sun [6] to increase the PSS quality and the profitability in this business. The economic analysis considers operational costs, cutting tool consumption, revenue from cutting tool recycling and investments to assess the economic viability of PSS implementation in machining. These parameters were defined based on the analysis of Mu et al. [3] that estimated the PSS cost of cutting tools. The literature on PSS in machining did not approach the environmental and social factors. For this reason, usual methods to quantify environmental and social impacts were adopted in this study. In environmental terms, the benefits to the ecosystem were measured by analyzing the mass balance of the recycling of cutting tools at the end of service life. Social advantages were related to occupational health and safety in terms of ergonomic risks reduction in the washing of tools. The Humantech software was used to calculate the ergonomic risk score.

4. Results

PSS analysis in machining was conducted in a diesel engine industry in São Paulo/Brazil. The factory has a quality management system (ISO 9001), environmental (ISO 14001) occupational safety and health (OHSAS 18001) certifications. Leadership stimulates its employees' professional and personal development as a human resources practice.

4.1. Presentation of the Production Process

The factory's production process consisted of four machining lines composed of manual machines, semi-automatic and CNC machining centres. Material handling between

machines is carried out by adopting unpulled roller tracks. The processing time from the raw part input to the output of the finished product is approximately 10 h.

Tool management considers two tool stocks: circulating and new. The first tool stock includes circulating, in-edging or preparation tools. The stock of new tools is adopted to replace the rolling tools at the end of service life.

Cutting errors are key factors to monitor for predicting the quality of the finished product. Cutting tool wear requires periodic changes to avoid quality issues such as scrap, rework. Monitoring the tools service life has been ensured by recording specific data and promptly signalling the tool change needed to the operators.

The complexity of tool acquisition flow strongly affected the machining performance. In this regard, the requests for new tools enter the purchase queue and require three managers' quotations and authorization. The various stages of this process take an average of seven days to complete. Another aspect that makes it difficult to manage tools is that the large number of suppliers lead to congestion in tool delivery tasks.

About the equipment for sharpening and preparing tools has emerged that these tasks are very complex and require highly skilled workers.

4.2. The PSS Implementation

A PSS contract has been suggested to the company's managers by the tooling supplier. The prospect of increased production demand and consequent consumption of tools, combined with failures of inventory management of tools and specialized labour to prepare tools, motivated the interest in the new business model.

Evaluating tools wear related to the service life of tools was key to identifying the tool consumption and the respective cost per part produced. Implementing RFID technology in tool management increased the reliability of the tools' information logging and consumption control. The preliminary analysis phase of the PSS lasted five years. In this period, the knowledge of the process was deepened, reducing the price uncertainties of the PSS and strengthening the trust of the customer-supplier relationship. From the PSS agreement signed, the client company has left the management of cutting tools in charge of the supplier. In the PSS, instead of buying the tool, the customer paid an agreed amount of tool consumption per piece produced.

In addition to the use of a tool, the PSS contract included the provision of specialized labour services in preparation, edging, material purchase, inventory control, engineering support, and productivity improvements related to cutting tools in the machining process.

The service life and the corresponding acquisition cost vary according to the type of tool. The tool life was defined according to practical tests performed in the machining process. Experts conducted tests on all tools repeated three times in each operation to analyze the machining process variations. The service life is given from the average of the three values measured reduced of a "safety factor" (i.e., 2%) introduced to avoid tool breakage and product quality problems. The service life information allows estimating the number of parts produced with the same tool. Therefore, the cost of tool per piece (CPP) was estimated according to Equation (1).

$$CPP = \sum_{t=1}^n \frac{\text{Tool cost } t}{\text{Tool life}} \quad (1)$$

where:

"t" represents the number of produced parts with a tool [unit];

"Total cost" is the cost of the tool considered [US\$];

"Tool life" identify the number of cycles performed by the tool before replacing [cycle].

An example of a part requiring 81 types of cutting tools to be machined is shown below (Table 3).

Table 3. Cost per piece of each tool.

ID Code	Description	Qty [u]	Tool Life [Cycle]	Tool Cost [US\$]	Cost per Piece [US\$/u]
#01	Drill Ø20 mm	1	282	136.00	0.48
#02	Countersink tool Ø15 mm	1	1120	558.00	0.50
#03	Step drill Ø4.5 mm	1	4000	320.20	0.08
#04	Blade 32 mm	1	340	29.70	0.09
#05	Drill Ø8.5 mm	1	1760	294.50	0.17
...	...	1	...	...	...
#81	Reamer 22 mm	1	2000	220.00	0.11
Total					14.60

The cost of US\$14.60 per piece represents the amount that the tool supplier will receive from the customer for each part produced on the machining line. In this example, assuming a scenario in which the annual volume of production is 20,000 pieces, the cost of cutting tools would be US\$ 292,000 per year or US\$ 5615.38 per week. The tool consumption cost is weekly estimated, according to the production of seven days, aiming to mitigate production fluctuation in relation to the annual planning. The withdrawal of tools from stock to production takes place adopting a requisition that generates the issuance of an invoice. The cost of specialized labour for the management and preparation of tools was US\$ 50,200 per month.

4.2.1. Tool Preparation in PSS

Old machines were adopted to prepare the tools. The tool supplier diagnosed the obsolescence of available machines, requiring the sector's modernization for the PSS implementation. Therefore, an investment of US\$ 820,000 was needed to acquire new machines and upgrade the available equipment. The preparation of tools was installed in the centre of the factory to facilitate the access and service to machining. Experts in cutting tools (employees of supplier) supporting machining process in production shifts are available on-site. In addition to infrastructure improvements, the control of readiness data has been modernized. The installation of RFID chips in tools allowed the storage and easy access to pre-set information, tool life, and tool identification. Therefore, when the tool in the CNC machining centre is installed, the data stored on the chip are automatically transferred to the machine without the intervention of the operator. This feature automatically loads the machining process at the end of the cutting tool service life, reducing tool breaks and product quality issues. In PSS, the tool replacement time was shortened from seven days to 20 min. The technician produces a requisition that contains the description of the tool and the reason for the reset. After the Production Leader has been approved, the technician registers the requisition in the tool management system and automatically removes a new tool from inventory.

4.2.2. Tool Inventory Management

The stock of tools is composed of new and circulating tools. A machine called Vending Machining (VM) manages 70% of items and could allocate more than 600 items such as inserts, blades, drills, and taps. VM works as a vendor sales station located in the tool preparation room. The tool requisition is electronically registered in the system, issuing an invoice, and sending it to the customer for weekly settlement with the supplier.

The minimum number of tools in stock has been identified for each item to avoid a lack of tools. Upon reaching the minimum stock, the system automatically generates a purchase order and sends it to the tool supplying plant to arrange inventory replacement. The tool requisition and reset steps are shown in Figure 3.

Figure 3. Tool requisition and retooling steps. Source: Elaborated by the author.

4.3. Economic Assessment

The economic feasibility of the business model was assessed to evaluate the eco-efficiency of the PSS in machining. The investment consisted of the tool preparation room, equipped with: two core sharpeners; three rapid steel, carbide and lapping grinders; one multi-sharpener; two tool presetters; one cylindrical grinder; two flat grinders; one automatic washer; two granite tables (straightening). The total investment in machinery and equipment was US\$ 820,000.

The machining cost reduction has been evaluated considering the entire PSS process, from tool stock management to tool consumption in production. In the PSS, the supplier ensures US\$1360,000 immobilized in tool stock. Where the tools included in the circulating stock (in the process) account for US\$ 560,000 of the total tools stocked. The tool consumption for the annual production volume of 20,000 pieces was estimated at US\$ 880,000 per year. The labour cost in inventory management and tool preparation was reduced from US\$ 794,880, before the PSS implementation, to US\$ 602,400 adopting the PSS. The recovery of metallic tool material due to recycling of cutting tools at the end of service life provided revenue of US\$ 5600 per year to the company. A summary of the data analyzed for the economic evaluation is provided in Tables 4 and 5.

Table 4. Economic evaluation before and after PSS implementation.

Description	Before [US\$]	After [US\$]	Annual Saving [US\$]	Monthly Saving [US\$]
Cost of cutting tool inventory	1,360,000.00	0		
Cost of cutting tool consumption	680,000.00	880,000.00		
Cost of cutting tool in process	408,000.00	560,000.00		
Labor	794,880.00	602,400.00		
Revenue from recycling	0	−5,600.00		
Total	3,242,880	2,036,800.00	1,206,080.00	100,506.67

The implementation of the PSS led to an annual reduction of US\$ 1,206,080 in operating cost per year, or US\$ 100,506.67 per month. The payback calculation indicated that the investment of US\$ 820,000 due to modernization of the tool preparation room will be recovered in nine months.

Table 5. Cash flow due to PSS implementation.

Cash Flow	Month 0	Month 1	Month 2	Month 3	Month 4
Total investment	−820,000.00				
Additional net profit		100,506.67	100,506.67	100,506.67	100,506.67
Accumulated net cash flow	−820,000.00	−719,493.33	−618,986.67	−518,480.00	−417,973.33
Cash flow	Month 5	Month 6	Month 7	Month 8	Month 9
Total investment					
Additional net profit	100,506.67	100,506.67	100,506.67	100,506.67	100,506.67
Accumulated net cash flow	−317,466.67	−216,960.00	−116,453.33	−15,946.67	84,560.00

4.4. Environmental Assessment

The cleaner production practice incorporated into PSS tool management allowed the recycling of tool material at the end of service life. This action contributed to the reduction of the extraction of virgin material and to the conservation of the ecosystem. The material of cutting tools is composed of 81% Tungsten, 13% Cobalt and 6% Carbon.

The mass balance analysis identified 602 kg of material destined for recycling in 2020. Therefore, the recovered cutting tools reduced the yearly exploitation of 487.6 kg of tungsten and 78.3 kg of cobalt. This result is even more expressive because it deals with scarce metals.

4.5. Social Assessment

The social factors were assessed considering the PSS implementation in machining. In particular, the tool washing activities involved health risks for operators due to ergonomics and chemical handling. The tools to be prepared should be washed in advance to remove a semi-synthetic metalworking fluid used in the machining process. According to the cutting tools supplier, the lubricant fluid specification was suitable for its purpose. It has an essential role in improving the surface finish of parts and extending tool life. The fluid was Quakercool 3605 BFF water-soluble. Before PSS implementation, the washing of the tools occurred in a reservoir in which the operator used a hose with a squirt and bristling brush. According to experts, these tasks produce efforts in the arms region at risk of injury. In this regard, the modernization that occurred with the implementation of the PSS provided a reduction in the risk to human health.

A washer machine automatically cleans and dries the tool in the new process. The operator works in the supply and removal of parts from the machine. With this, human contact with the chemical agent was eliminated and, efforts in the arms were significantly reduced.

The advantages achieved for human health were evaluated by Risk Priority Score (RPS) estimated adopting a software used in ergonomic analysis. The comparative risk analysis before and after the PSS implementation is shown in Figure 4.

Figure 4. Ergonomic Evaluation. Source: Elaborated by the author.

4.6. PSS Opportunities and Threats in Machining

Company managers have positively evaluated the PSS. The increase in technical knowledge due to the incorporation of tools' experts in the production process provided economic, environmental, and social gains.

However, the PSS risk factors were raised to mitigate a negative impact on business. One aspect mentioned by managers is that the technical knowledge of cutting tools was under the supplier's domain. Moreover, although the supplier is a world reference in the manufacture of cutting tools, there is a risk of limitation to the technologies adopted.

In addition, considering the vulnerability of technical knowledge, there is a risk related to the financial capacity of the supplier. The threat to the company arises from the possibility of the supplier going bankrupt or giving up the business. The impact on financial risk was mitigated by contract clauses that define the supplier's obligation to approve another supplier of cutting tools to meet the customer's demand. In addition, periodic meetings between the senior management of the companies are conducted every six months to present the results, including the supplier's financial condition.

5. Discussion

The results of this study showed that the diagnosis of technological lag in the preparation of tools, elaborated by the supplier, opened the mind of the senior management to the need for investments in this area. The acquisition of machinery and equipment increased the reliability of tool preparation, reducing non-quality costs and ensuring technicians' safer operation. With this, PSS in machining proved to be aligned with advances in sustainable development. This finding corroborates the study by Oliveira Neto et al. [15] on machine modernization as a strategy aimed at sustainable development goals, #9 (Industry, innovation and infrastructure) and #12 (sustainable production and consumption) of the United Nations agenda 2030.

The previous analysis period to PSS implementation was fundamental to improving knowledge on the production process. In this stage, the conditions monitoring of machining and tool preparation provided data that made it possible to establish the fair cost of tool per piece for both buyer and supplier. This finding corroborates Zhang and Sun [6] that developed a cutting tool condition monitoring model to increase the PSS quality and the profitability in this business.

Another fact was the reduction of production downtime due to the lack of a cutting tool. This achievement was due to the responsibility of cutting tools management move from customer to supplier. The supplier's stock at the customer site reduced communication noise, increased the sense of priority and the availability of cutting tools. The outsourcing management of cutting tools reduces costs and improves productivity [13].

Another positive aspect linked to PSS was the implantation of cleaner production practices in machining. The uniqueness in supplying tools increased the attractiveness of hard metal recycling. The sale of the recovered material at the end of life (before the PSS implementation was discarded), is an additional revenue and reduces the extraction of virgin raw material. The conservation of the ecosystem carried out by reducing environmental impact is inserted in the companies' environmental policy focused on this study. Therefore, the involvement of suppliers adopting environmental practices helped both related companies in the business achieve sustainable development goals, as stated by Oliveira Neto et al. [20].

The economic evaluation conducted in this study considered an investment for the implementation of the PSS, including labour, inventory costs and tools consumption. This information was fundamental to evaluating the economic viability of the PSS. The method used in this research converges with the PSS costs estimation introduced by Mu et al. [3], in which the pricing parameters were evaluated considering the same item costs.

Despite the economic assessment showing the return on investment within nine months, PSS is usually characterized by long-term contracts. PSS is based on trust, enhancing the importance of buyers and suppliers seeking to strengthen dialogue and cooperation

to reduce business uncertainties. The PSS risk management mentioned by managers in the case study revealed the business model's concern. PSS contracts' uncertainties were analyzed by Farsi and Erkoyuncu [8] that highlighted that PSS is advantageous in long-term contracts.

The advantages achieved highlighted a strong relationship with the tools supplier led to improving the eco-efficiency of machining. The economic viability of the PSS presented in this work revealed that the payment for the use of the tools instead of its acquisition reduced inventory cost, inventory replacement time and reduced the risk due to lack of tools.

6. Conclusions

This study achieved its objective of evaluating the economic, environmental, and social advantages of PSS cutting tools in machining. The results indicated that the PSS in machining is an eco-efficient alternative for sustainable development in the industry. The PSS reduced the operating cost of US\$ 1,206,080 per year, which allowed the return on investment in nine months. In addition, recycling 602 kg of carbide per year reduced the extraction of scarce metals in nature, such as tungsten and cobalt. Furthermore, technological advances reduced the risk of injury to operators. These advantages shown that PSS in machining is a cost-effective business model that provides environmental and social benefits.

These findings denoted that PSS cutting tools in machining meets two sustainable development goals. The evidence of goal number 9 (industry, innovation and infrastructure) achievement was the modernization of the tool preparation room. The acquisition of new machines and equipment increased the productivity of tool preparation. Furthermore, the RFID technology implementation improved the data reliability of the stock management system and reduced product quality issues. The other goal, number 12 (responsible consumption and production), highlighted the optimization of cutting tool consumption and the recycling of cutting tools at the end of the life cycle.

The theoretical contribution of this research was to provide a work not yet detailed in the scientific literature on the economic, environmental, and social advantages of PSS in machining. PSS as a contemporary business model should fulfil the sustainability requirements demanded by stakeholders. However, the systematic literature review on PSS in machining identified that environmental and social factors were neglected in published studies. This finding shows the opportunity for future research to investigate the socio-environmental implications of PSS in the machining process. Moreover, an in-depth analysis can reveal that PSS drives sustainable development in other industrial sectors.

As a contribution to corporate practice, this study aims to encourage industrial managers to seek PSS businesses that increase the eco-efficiency of their production processes. The dissemination of this work can reach managers of suppliers and customers and encourage them to promote strategies aimed at replacing product ownership with the service of their use. The approximation of business partners with socio-environmental goals allows a synergy between factories to implement cleaner production practices aimed at sustainable development.

The exploratory purpose of this research limited its findings to the company focused on the study. The method and data collected do not allow the generalization of the results. Another limitation of this study is the focus on sustainable development goals #9 (industry, innovation and infrastructure) and #12 (responsible consumption and production). These goals are related to industrial activity. In this sense, future studies should explore PSS in machining under different perspectives taking into account other goals defined by the United Nations Organization. In addition, future research should be addressed to more extensive studies, where a great number of companies should be included. Moreover, more deep knowledge about PSS in machining advantages should promote sustainable development, considering all supply chain stakeholders.

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Appendix A

Table A1. List of papers found in literature review about PSS and cleaner production.

#	Authors	Article Title	Journal	Year
1	Pecorari, P.M.; Lima, C.R.C.	Correlation of customer experience with the acceptance of product-service systems and circular economy	Journal of Cleaner Production	2021
2	Chiu, M.; Huang, J.; Gupta, S.; Akman, G.	Developing a personalized recommendation system in a smart product service system based on unsupervised learning model	Computers in Industry	2021
3	Farsi, M.; Erkoyuncu, J.A.	Na agent-based approach to quantify the uncertainty in product-service system contract decisions: a case study in the machine tool industry	International Journal of Production Economics	2021
4	Bu, L.; Chen, C.; Ng, K.; Zheng, P.; Dong, G.; Liu, H.	A user-centric design approach for smart product-service systems using virtual reality: A case study	Journal of Cleaner Production	2021
5	Chang, F.; Zhou, G.; Zhang, C.; Ding, K.; Cheng, W.; Chang, F.	A maintenance decision-making oriented collaborative crossorganization knowledge sharing blockchain network for complex multi-component systems.	Journal of Cleaner Production	2021
6	Siguenza, C.P.; Cucurachi, S.; Tukker, A.	Circular business models of washing machines in the Netherlands: Material and climate change implications toward 2050.	Sustainable Production and Consumption	2021
7	Joensuu, T.; Edelman, H.; Saari, A.	Circular economy practices in the built environment	Journal of Cleaner Production	2020
8	Salwin, M.; Kraslawski, A.; Lipiak, J.; Golebiewski, D.; Andrzejewski, M.	Product-service system business model for printing houses	Journal of Cleaner Production	2020
9	Wang, N.; Ren, S.; Liu, Y.; Yang, M.; Wang, J.; Huisingh, D.	An active preventive maintenance approach of complex equipment based on a novel product-service system operation mode.	Journal of Cleaner Production	2020
10	Joensuu, T.; Edelman, H.; Saari, A.	Circular economy practices in the built environment	Journal of Cleaner Production	2020
11	Ivanov, V.; Trojanowska, J.; Pavlenko, I.; Zajac, J.; Peraković, D.	3rd International Conference on Design, Simulation, Manufacturing: The Innovation Exchange, DSMIE 2020	Lecture Notes in Mechanical Engineering	2020
12	Pacheco, D.A.J.; Caten, A.S.; Jung, C.F.; Navas, H.V.G.; Cruz-Machado, V.A.; Tonetto, L.M.	State of the art on the role of the Theory of Inventive Problem Solving in Sustainable Product-Service System: Past, Present and Future.	Journal of Cleaner Production	2019

Table A1. Cont.

#	Authors	Article Title	Journal	Year
13	Zhang, A.; Chai, N.; Ostrosi, E.; Shang, Y.	Extraction of association rules in the schematic design of product service system based on Pareto-MODGDFA	Computers & Industrial Engineering	2019
14	Liu, B., Zhang, Y., Zhang, G., Zheng, P.	Edge-cloud orchestration driven industrial smart product-service systems solution design based on CPS and IIoT	Advanced Engineering Informatics	2019
15	Sousa-Zomer, T.T.; Magalhães, L.; Zancul, E.; Campos, L.M.S.; Cauchick-Miguel, P.A.	Cleaner production as an antecedent for circular economy paradigm shift at the micro-level: Evidence from a home appliance manufacturer.	Journal of Cleaner Production	2018
16	Chang, F.; Zhou, G.; Xiao, X.; Tian, C.; Zhang, C.	A function availability-based integrated product-service network model for high-end manufacturing equipment	Computers & Industrial Engineering	2018
17	Zhang, G.; Sun, H.	Enabling a cutting tool iPSS based on tool condition monitoring	International Journal of Advanced Manufacturing Technology	2018
18	Zhang, G.; Sun, H.	Enabling cutting tool services based on in-process machining condition monitoring	International Journal of Internet Manufacturing and Services	2018
19	Souza-Zomer et al.	Cleaner production as an antecedent for circular economy paradigm shift at the micro-level: Evidence from a home appliance manufacturer	Journal of Cleaner Production	2018
20	Sopelana, N., Gonzalez, L., Lazaro, O., Laskurain, A., Minguez, R.	Circular engineering and product-service systems in the machine tool sector: The PSYMBIOSYS approach	Enterprise Interoperability: Smart Services and Business Impact of Enterprise Interoperability	2018
21	Mourtzis, D., Fotia, S., Boli, N., Pittaro, P.	Product-service system (PSS) complexity metrics within mass customization and Industry 4.0 environment	International Journal of Advanced Manufacturing Technology	2018
22	Peruzzini, M.; Pellicciari, M.; Bil, C.	25th ISTE International Conference on Transdisciplinary Engineering, 2018	Advances in Transdisciplinary Engineering	2018
23	Sousa-Zomer, T.T.; Magalhães, L.; Zancul, E.; Cauchick-Miguel, P.A.	Lifecycle management of product-service systems: a preliminary investigation of a white goods manufacturer	Procedia CIRP	2017
24	Wan, S.; Li, D.; Gao, J.; Roy, R.; Tong, Y.	Process and knowledge management in a collaborative maintenance planning system for high value machine tools	Computers in Industry	2017
25	Auer, J.; Bey, N.; Schafer, J.	Combined life cycle assessment and life cycle costing in the eco-care-matrix: A case study on the performance of a modernized manufacturing system for glass containers.	Journal of Cleaner Production	2017
26	Mu, H., Jiang, P., Leng, J.	Costing-based coordination between mt-iPSS customer and providers for job shop production using game theory	International Journal of Production Research	2017
27	Uhlmann, E., Hohwieler, E., Geisert, C.	Intelligent production systems in the era of industrie 4.0-Changing mindsets and business models	Journal of Machine Engineering	2017

Table A1. Cont.

#	Authors	Article Title	Journal	Year
28	Sun, P., Zhang, C., Jiang, P., Cao, W.	Cutting-tool delivery method in the context of industrial product service systems	Concurrent Engineering Research and Applications	2016
29	Weißfloch, U., Geldermann, J.	Assessment of product-service systems for increasing the energy efficiency of compressed air systems	European Journal of Industrial Engineering	2016
30	Uhlmann, E., Gabriel, C., Raue, N.	An automation approach based on workflows and software agents for industrial product-service systems	Procedia CIRP	2015
31	Selak, L.; Butala, P.; Sluga, A.	Condition monitoring and fault diagnostics for hydropower plants	Computers in Industry	2014
32	Settanni, E.; Newnes, L.B.; Thenent, N.E.; Parry, G.; Goh, Y.M.	A through-life costing methodology for use in product-service-systems	International Journal of Production Economics	2014
33	[No author name available]	IFIP WG 5.7 International Conference on Advances in Production Management Systems, APMS 2014	IFIP Advances in Information and Communication Technology	2014
34	Liedtke, C., Buhl, J., Ameli, N.	Microfoundations for sustainable growth with eco-intelligent product service-arrangements	Sustainability	2013
35	Lv, Z., Miao, R., Wang, S.	The application of six sigma management in product service system	International Asia Conference on Industrial Engineering and Management Innovation: Core Areas of Industrial Engineering, IEMI 2012—Proceedings	2013
36	Mu, H.; Jiang, P.; Zhu, Q.	Machining process level cost estimation in cutting-tool IPSS	Applied Mechanics and Materials	2012
37	Vezzoli, C., Ceschin, F., Diehl, J.C., Kohtala, C.	Why have ‘Sustainable Product-Service Systems’ not been widely implemented? Meeting new design challenges to achieve societal sustainability	Journal of Cleaner Production	2012
38	Lelah, A.; Mathieux, F.; Brissaud, D.	Contributions to eco-design of machine-to-machine product service systems: the example of waste glass collection.	Journal of Cleaner Production	2011
39	Schuh, G., Potente, T., Schittny, B., Wittek, A.	Industrial product-service-systems for the tooling industry	17th International Conference on Concurrent Enterprising, ICE 2011—Conference Proceedings	2011
40	Zhu, Q.Q., Jiang, P.Y.	Machining capacity measurement of an industrial product service system for turning processg	Proceedings of the Institution of Mechanical Engineers, Part B: Journal of Engineering Manufacture	2011

Table A1. Cont.

#	Authors	Article Title	Journal	Year
41	Sun, H., Wan, N., Chang, Z., Mo, R.	Approach to optimization of part machining service combination	International Journal of Advanced Manufacturing Technology	2011
42	Abramovici, M., Lindner, A.	Providing product use knowledge for the design of improved product generations	CIRP Annals—Manufacturing Technology	2011
43	Zhu, Q.Q., Jiang, P.Y., Huang, G.Q., Qu, T.	Implementing an industrial product-service system for CNC machine tool	International Journal of Advanced Manufacturing Technology	2011
44	Zhu, Q., Jiang, P.	Operations of an industrial product service system based on machine tool at user factory	Proceedings—2010 International Conference on Digital Manufacturing and Automation, ICDMA 2010	2010
45	Uhlmann, E., Geisert, C., Stelzer, C.	Software agent based monitoring for a micro milling spindle	Proceedings of the 10th International Conference of the European Society for Precision Engineering and Nanotechnology, EUSPEN 2010	2010
46	Zhu, Q., Jiang, P., Zheng, M., Zhang, D.	Modelling machining capabilities of an industrial product service system for a machine tool	International Journal of Internet Manufacturing and Services	2010
47	Clark, G., Kosoris, J., Hong, L.N., Crul, M.	Design for sustainability: Current trends in sustainable product design and development	Sustainability	2009
48	Zhu, Q.-Q., Jiang, P.-Y., Zhang, P., Wang, X.-X.	Configuration and operation architecture for product service systems of CNC machine tools	Jisuanji Jicheng Zhizao Xitong/Computer Integrated Manufacturing Systems, CIMS	2009
49	Jiang, P., Fu, Y., Zheng, M.	Using iPSS as a new run-time for service-oriented manufacturing executivesystems	2009 International Conference on Computers and Industrial Engineering, CIE 2009	2009
50	Jiang, P., Fu, Y.	A new conceptual architecture to enable iPSS as a key for service-oriented manufacturing executive systems	International Journal of Internet Manufacturing and Services	2009
51	Baxter, D., Roy, R., Doultsinou, A., Gao, J., Kalta, M.	A knowledge management framework to support product-service systems design	International Journal of Computer Integrated Manufacturing	2009
52	Yoo, S.D.	1st EU-Korea Conference on Science and Technology, EKC 2008	Springer Proceedings in Physics	2008
53	Vezzoli, C.; Sciama, D.	Life Cycle Design: from general methods to product type specific guidelines and checklists: a method adopted to develop a set of guidelines/checklist handbook for the eco-efficient design of NECTA vending machines.	Journal of Cleaner Production	2006

Table A1. Cont.

#	Authors	Article Title	Journal	Year
54	Mont, O.	Editorial for the special issue of the Journal of Cleaner Production on Product Service Systems	Journal of Cleaner Production	2003
55	Maxwell, D.; Van der Vorst, R.	Developing sustainable products and services	Journal of Cleaner Production	2003
56	Solgaard, A.	Promoting a life-cycle approach	Industry and Environment	2002
57	Roy, R.	Sustainable product-service systems	Futures	2000

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