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Analyzing the risks of digital servitization in the machine tool industry

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ABSTRACT

The machine tool industry plays a major role in the execution of high-quality and efficient complex manufacturing processes. The adoption of digital technologies can transform production systems into more connected, adaptive, efficient, and potentially sustainable systems. A key enabler of this transformation is servitization, a business model that builds on digitalization and data capture to deliver value through services. Digital services for machine tools typically use data obtained through highly connected manufacturing environments, providing visibility of complex lifecycles, and enabling better decision-making. However, an understanding of digital servitization to support the machine tools industry is still emerging and for most industrial actors the potential risks are unclear. The findings of this study describe potential applications of digital servitization in the machine tool industry, synthesize the identified risks from practitioners' perspectives, and provide mitigation and contingency activities. This study contributes to bridging the gap between theory and practice by clarifying companies' needed considerations before implementing digital services in the machine tool industry.

1. Introduction

Machine tools are key assets in production [1] because they interact with virtually everything that is being manufactured [2]. Their role in the manufacturing industry is central and their performance has a direct impact on product quality and production efficiency [3]. According to CECIMO [4], an average of 80% of machine tools are still in service ten years after their installation, and 65% are still in service after 20 years, making them durable products with long lifecycle times and good candidates for business models that enable lifecycle extension, such as digital servitization.

Although the connections between digitalization, servitization, and sustainability cannot be taken for granted [5], intersections are found in the machine tool industry. For instance, Xu [2] suggested that machine tools are no longer isolated manufacturing equipment. Machine tool manufacturers can be solution providers, leaving room for the exploration of digital services in this context. Digital services are defined as "new services provided through digital technologies that exploit the connectivity of products to create value via digitally enhanced provider-customer relationships" [6]. In the machine tool industry, digitalization drives the convergence between machine tools and other fields, as it is increasingly exposed to services from machine control manufacturers, periphery equipment, factory automation players, software companies, Internet of Things (IoT) platform providers, among others. Digital services can take advantage of increased connectivity, IoT and other digital enablers to better provide decision-making support and enable sustainability by improving energy efficiency, allowing companies to avoid or reduce waste in the form of defects and scrap, while extending tools' lifetime, and improving product quality [7].

Servitization, which in this manufacturing context refers to digital servitization, has acquired increased relevance given evidence of product-centred business models not being sufficient to achieve success [8]. For instance, Bakås et al. [9] have announced the "golden age of services", and that "every company must transform into a service business" to survive and prosper. Some of the potential benefits of digital servitization include supporting companies in increasing their offerings portfolio, generating additional revenue and profits, retaining customers, and engaging with new ones in tighter relationships [10,11].

The integration of product and service lifecycles is still an unclear process where most companies need new ways to combine efficiently the innovation processes [12,13]. This mismatch between lifecycles poses one of the biggest challenges for digital servitization as such

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synchronization requires improvements in several types of data and information managed by PSS providers [14], along with knowledge formalization, collection, sharing, and reuse among product design and service management functions [11,15,16]. Also, servitized offerings have redefined internal core business functions [17], where poor understanding of how to successfully deliver digital services leads companies to the so-called "service paradox" [11,16,18], where investments to extend the service business lead to increased service offerings and higher costs, but do not generate the expected economic or environmental benefits [10,11,16]. Such paradoxes highlight the need for short and agile innovation processes that avoid over-commitment towards investments in large, complex, digital service systems that become outdated or overpriced before their full development [19].

The perceived risks of digital servitization face dual opinions. On the one hand, some authors identify potential benefits, such as increased sales revenues, reduced risks for customers and enabled predictive maintenance [20]. On the other hand, the exploration of the challenges associated with the inclusion of services in previously product-centred offerings, including the risks of servitization in manufacturing companies, are documented in literature mainly from a theoretical and descriptive perspective, lacking consensus in the categorization of the risks and their potential implications [21]. This study identifies a lack of understanding of how risks are perceived for specific digital services, failing to inform the machine tool industry about the potential negative implications of digital servitization in their industrial context.

Based on the identified research gap, this study poses the following research question:

What are the risks associated with the adoption of digital servitization in the machine tool industry?

To address this research question, we developed three digital services and assessed the potential risks associated with their implementation, as well as identified mitigation and contingency activities.

The remainder of this paper is organized as follows. Firstly, literature on servitization and digitalization is introduced and contextualized in the machine tool industry. Secondly, the case study and the involved stakeholders are described. Thirdly, the results including the description of the services and the risk assessment are presented. Fourth, the discussion section presents a comparison of the risks identified with relevant literature and provides mitigation and contingency activities. Last, the conclusions are presented.

2. Theoretical framework

Digitalization is the most important engine of innovation, competitiveness and economic growth in the world, and an enabler of new and more sustainable business models, such as servitization. Both digitalization and servitization are known to be adopted by firms in their attempt to become more sustainable and respond to the growing pressures of governmental regulations and stricter customer demands. However, the connection between digitalization and servitization is unclear. The next Section 2.1 highlights theoretical contributions from the literature and describes the intersection between digitalization, servitization and sustainability. Then Section 2.2 contextualizes this conceptual intersection within the machine tool sector. Last, Section 2.3 presents risks identified for digital servitization.

2.1. Digital servitization and its role in achieving sustainable manufacturing

The increasing environmental concerns are creating a new competitive framework [22], particularly in the production and manufacturing sector [23], where digitalization and servitization support manufacturing companies in addressing sustainability imperatives [5]. This has led to a new field of literature called "digital servitization", defined as the provision of digital services which rely on digital components embedded in physical products [24–26].

On the one hand, digitalization refers to increased data availability, accessibility, interoperability, connectivity, and efficient data communication, computation, and storage that allow easier delivery and manipulation of a product or service [3,27]. Further, the concept of Industry 4.0 refers to a transformation where sensors, machines, workpieces and IT systems [28] enabled by the Internet of Things (IoT) and cloud platforms, enable service-oriented, digitalized and sustainable business models that revolutionize complete value chains [29]. An example of the possible effects of such transformation lies in the way that lifecycle data results in the possibility of a more efficient, flexible and practical performance, covering precise customer needs [30,31].

On the other hand, *servitization,* first introduced by Vandermerwe and Rada [32], refers to solutions where products and services are integrated [33], such as advanced data analytics and visualization [34], high-fidelity simulation and prediction, intelligent decision-making support, and human-machine interaction [35]. Servitization holds the potential to extend value from product-centred to service-centred offerings [10], such as creating firmer and tighter relationships with customers, having more precise value propositions, and becoming solution-oriented. In their work, Rust and Huang [36] state that, “the service revolution and the information revolution are two sides of the same coin”, where servitization is considered a data-intensive transformation of the manufacturing industry [34]. Nevertheless, the way servitization enables the commercialization of data and information has only been explored to a limited extent [34], where few contributions address the use data from sensors in production systems to monitor units and develop sustainability-oriented services [37].

Companies are increasingly interested in digital servitization as they expand their offerings with digital services to achieve increased functionality, better reliability, higher product utilization, and capabilities previously considered beyond product boundaries while generating additional revenues and profits, and potentially gaining and sustaining a competitive advantage [38,39]. In the past, products were composed mainly of mechanical and electrical parts, but today most manufacturers produce complex systems. This transition comes along with top management challenges, that require companies to change their strategies and build new business concepts at several stages that range from product design, marketing, manufacturing and after-sale services, and also by creating the need for new activities such as product data analytics and security [40].

Based on documented evidence that a linear economy is not sustainable in the long term [41], this study investigates how digitalization can be a positive asset in the transition towards more sustainable business models [42,43], that consider three principles of a more circular economy [44] namely, (1) extending the lifecycles of the products that are manufactured with non-renewable resources, (2) designing out waste and (3) regenerating natural systems. Their integration as guidelines in the planning of future production systems for more sustainable manufacturing is both a theoretical and practical imperative [45].

2.2. Servitization and digitalization in the machine tool industry

The increasing body of research on digitalization and servitization of machine tools [3] has enabled process optimization, increased efficiency and reduced waste through new phases of automation, as well as the development of creative and efficient products and services leading towards more intelligent production systems, reshaped business models and improved value creation strategies [46].

The machining sector is highly relevant as machine tools are necessary all stages of manufacturing processes. Companies in this industrial sector are involved in the process design, development, technical assistance, and provision of solutions to customers. The life span of almost 30 years for machine tools could benefit from exploring product-service system (PSS) approaches, where after the OEM guarantee period, service providers acquire and possibly retrofit the machines and sell, rent, or lease them to their customers and provide services based on PSS contract agreements [47].

The demand for virtualization highlights the need for digitalization. This is a complex task since machine tools are a heterogeneous group of products, often empirically designed through a trial and error approach [48], with high levels of customization, variety of size and materials that they are capable of machining, various levels of automation, speed and performance [4].

The new generation machine tools (also referred to as Machine Tool 4.0 [49]) is said to feature an extensive implementation of CPS, IoT, sensors, computing technologies and incorporate network connectivity, flexibility, foreseeability of intelligence, and real-time response loops [49]. The era of big data-driven manufacturing, alters machine tools and converts them into intelligent assets, completing the digitalization and servitization of machine tools [46,50].

From the technological perspective, smart technologies could be used to identify the improper use of machines and prevent human errors, evading inactivity and workplace injuries [46,51], providing better control and traceability of the manufacturing process and supporting more sustainable working structures [52]. The incorporation of digital technologies in the machine tool industry could guide a faster industrial transformation process, simplifying the improvement of machine tools' quality in less time and at a lower cost [46]. Furthermore, a digitalized machine tool industry can also shift the market, enabling effective responses to the changing customer demands and improving the quality and sustainability of the offered services [53].

Through digital services, servitization can support manufacturers by improving customer relationships; creating growth opportunities in matured markets, balancing the effects of economic cycles with different cash flows [54], and monetizing value [26] by developing business models where customers' payments are based on performance or results instead of the purchasing of equipment [55]. Based on emerging cloud technologies, service-oriented system architectures allow the sharing and distribution of field-level machine tool data, enabling manufacturing services to be efficiently generated, transmitted, and provided to the cloud [56–58]. Therefore, machine builders would need to change from being machine suppliers to manufacturing process partners with their customers [59].

Recent literature addresses the lack of support for the machine tool industry to adopt digitalization practices by proposing an industry-specific Industry 4.0 Maturity Matrix, identifying the absence of case-specific literature as a major obstacle to successfully customising and implementing Industry 4.0 in practice [59]. Further, the authors attempted to tackle the lack of IT integration and adoption of software-based analytical tools, along with the lack the confidence to handle data management and security, challenges often faced by SMEs, who must realize their readiness and maturity to employ and deploy digital technologies in both their equipment and products [60]. Hoffman et al. [61] relied on digital servitization to propose a stress-based leasing model for machine tools which relies on the monitoring of stress levels from different components, linking these to the occurred wear and monetizing the stress factor for a monthly leasing fee. Besides aiming for cost reductions for lessee and lessor, "Pay-per-Stress" intended to increase the visualization of operational insights and use machine tool data to further improve processes and products.

2.3. Risks associated with digital servitization in the machine tool sector

Since the late 1990s, literature has documented servitization challenges [62], including non-real-time, inaccurate and incomplete data presented in non-homogeneous formats, potentially resulting in operational inefficiencies, and inaccurate and unreliable decisions [63]. This study conceptualizes risks as proposed by Holzer and Millo [64], "fundamental uncertainty, at the time of risk-taking, one cannot know for sure whether the opportunity concerned will be realized; in the worst case, the costs incurred might be greater than any benefit".

In the context of digitalization firms continuously face traps or pitfalls where profitability is compromised as investments and cost increases that do not always lead to increased revenues [10]. Some identified risks in literature stem from three main traps: (1) limited understanding of customer value, (2) expecting additional gains with a poor understanding of the value delivery process and (3) lack of understanding of profit formulas [65]. Also, there is an added paradoxical pressure when trying to maintain manufacturing efficiency while seeking growth through the delivery of customized services [66].

The research on servitization risks was initially focused mainly on the financial outcomes of servitized businesses [20], including operational, and external risks [21]. Manufacturers are often described as "risk averse tending to prefer low-uncertainty situations [67]. The servitization and digitalization paradoxes are often perceived as high-risk transitions by manufacturers [68,69], where investments are done without receiving the expected revenue enhancements, and even leading to increased operational and overall fixed costs. Some of the main financial risks include problems related to price, credit, inflation, liquidity, and potential losses, most often caused by changes in financial markets and defaulting by large-scale debtors [70]. Also, digital services often shift the responsibility of the operation of equipment to the providers, as the corresponding revenues are determined by performance outcomes rather than ownership, exposing both providers and customers to new risks [65]. Further, the pricing of equipment availability requires the product-service providers to assume the operating risks [71] and requires the definition of a costing strategy that works in different time horizons and under high uncertainty situations.

Digital servitization can potentially increase the likelihood of unintended or unpredictable customer behavior that negatively impacts providers' operations through the modified use of hardware [65]. Contractual specifications can help to avoid some unexpected effects but require addressing the risks associated with the high level of customization that most digital services need. The current design of contracts from service providers in the machine tool industry relies mainly on upkeeping activities, deeming inadequate to enhance customers' satisfaction [47]. The upkeeping contracts are often based on corrective maintenance and previous experience, resulting in lower quality, higher cost, and longer downtime of the machine for maintenance. Designing a beneficial service contract to solve this gap can be relatively complicated and challenging considering the variety of machine tool types and the required understanding regarding their monitoring and performance. Further, contracts must be protected from opportunistic behaviour and unreliable predictions of sales volumes through "what-if" scenario development phases [65].

Machine tools often correspond to isolated systems, where machine tool data are kept at shop floor level, limiting the applicability of potential services only to localised options. Currently, the missing knowledge about tools wear state hinders process automation and incentivizes the waste of resources through automated tool changes with safety margins [72].

Most successful adopters of industry 4.0 are large companies, posing a challenge for the machine tool sector, as most of these companies in Europe are Small and Medium Enterprises (SMEs) that often find it more difficult to adopt digital technologies. This makes their transition towards digital servitization an urgent challenge to address [59]. Other risks and concerns from firms include, for instance, equipment connectivity and the availability of storage and processing capabilities for the large volumes of data generated by production assets. Also, security is one of the main concerns often precluding the adoption of digital technologies beyond factory walls. In this context, the capability to develop, integrate and offer software also acquires a bigger dimension, as the new services would be based on software applications [73].

3. Methods

This section describes the methods followed to explore potential applications of servitization and digitalization in the machine tool industry and to identify and analyze the empirically perceived risks. A case study was conducted, where qualitative data collection methods were selected to comply with the exploratory nature of this work. The six stages followed in this research process follow the process proposed by Yin [74] for case study research (Fig. 1).

3.1. Plan

In the stage **"plan",** a research question was defined after understanding the research context. As suggested by Yin [74], initial field observations, document reviewing, along with informal interviews took place to understand the circumstances fully, before conducting the case study. The research process began with a problem diagnosis and the definition of objectives through a collection of insights from a consortium of researchers and manufacturing experts.

This study involved two research organizations and three industrial companies, the industrial partners being the main users of the digital services. These companies were selected based on three main criteria: (1) interest in digital services, (2) expertise in machine tools and (3) willingness to invest time, cooperate and share information about the perceived risks. The companies' relationships with SMEs, as well as with large companies, as part of their commercial activities, were considered beneficial for the understanding of a more complete picture of the European machine tool market. A description of the three companies is presented in Table 1.

The primary application sector of this research work is the automotive sector and discretely machined components for Company A, which has specific interests in digitalization as they want to develop a virtual twin factory to shorten lead times to market and aim to develop standards and software tools for virtual preparation in a digitized factory. In the context of this research work, they attempt to use the digital service to minimize scraps and reworks through a "first-time-right" approach. The OEE (Original Equipment Effectiveness) of the production lines was optimised through production planning and Discrete Event Simulation models.

Then Company B, considered a global leader in the design and manufacture of advanced technologies, specializes in medium and large machines and complete turn-key solutions integrating all the requested technologies. This company aims to find benefits from the zero-defect manufacturing approach and the optimization of their overall through machine tools with thoroughly enhanced capabilities. Then, Company C, a global technology company world leader in automation, considers digitalization an enabler of new opportunities and believes that the CAM software can be supported through the developed process simulations in the developed digital services.

Table 1
Description of companies involved.

	Company A	Company B	Company C
Sector	Automotive manufacturer	Advanced manufacturing technology provider (specialized in high-performance CNC milling-boring & lathe machinery)	Advanced manufacturing technology provider (specialized in industrial automation)
Location	Headquarters in Sweden and a global presence	Spain	Headquarter in Germany and global presence (focused on Europe for this study)
Number of Employees	11,500	270	303,000
Revenue	11.02 billion Euros	100 million Euros	86.85 billion EUR
Industrial expertise represented (questionnaire respondent profile)	Senior researchers & technology development engineers	International research and innovation project managers and program managers	Senior engineers and research and development managers

3.2. Design and prepare

During the stage **"design"**, the case boundaries were defined by identifying the main stakeholders and the test scenarios. Qualitative data collection methods were selected to capture concerns from the industrial experts regarding the use of digitalization and servitization in the machine tool industry.

The stage "**prepare"** started with a literature review. Then the

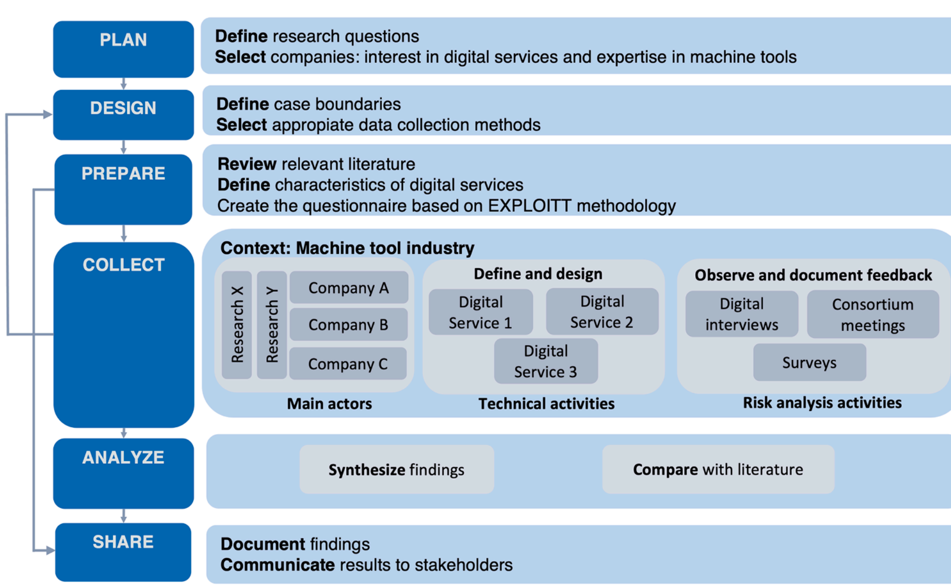


Fig. 1. Research process.

characteristics of the digital services (to be developed in the next stage) were defined based on the needs of the industrial companies, taking inspiration from action research to inform the collaboration on the diagnosis of the problem and the development of a solution [75].

The research protocol for the risk analysis was based on the EXPLOITT methodology of industrial exploitation (https://www.focusonfof.eu/downloads/results/methodology-industrial-exploitation-take-up.pdf), which was adapted to fit the context of this project. There is a shortage of resources that protect companies from mistakes and risks faced in the development of new technologies, particularly SMEs, a gap already identified and attempted to cover in literature by Schuh et al. in 2014 [76]; however, there is a perceived lack of focus in the industrial risks of digital services. On the other hand, the EXPLOITT methodology has the main objective of driving and finetuning technology development of effective industrial exploitation, prioritising innovation, exploitability, and industrial impact. This methodology is an outcome of a Horizon2020 project called Focus (https://www.focusonfof.eu/results.asp) and was found particularly useful as it was designed to understand the potential for exploitation of research-based developments in real industrial environments. Further, the European context of its development proved to be easily transferrable to this project.

The stage "**collect**" included technical activities and a risk analysis. As part of the technical activities, three digital services were developed by collecting inputs from the companies about their needs and goals, including some objectives related to sustainability and eco-efficiency [77]: (1) reduce defects, (2) avoid overproduction, and (3) reduce waiting times. The digital services are based on the use of principles of digital twins for process, machine, and production flow optimization, relying on servitization principles [78] to deliver value through digital services. The description of the digital services is included in Section 4.1.

As part of the risk analysis, the digital services were tested by experts from the project Consortium, based on the EXPLOITT methodology. The experts answered the digital questionnaire in two rounds. In the first round, the risks perceived were identified using a questionnaire with responses on a Likert scale [79] from 1 to 4 for risk likelihood and impact. The risks were categorized by three researchers into the following nine categories, which are part of the EXPLOITT methodology but adapted to fit the purpose of this research: (a) business, (b) project, (c) strategic, (d) legal, (e) team, (f) technical, (g) integration, (h) quality and (h) planning risks. Then, the responses were averaged to ensure anonymity between the industrial partners and presented in a risk matrix. The second round of the questionnaire identified the mitigation and contingency actions for the highest risks (based on likelihood and impact scores).

In the stage "**analysis"**, the results were compared, and the risk matrixes were developed based on the feedback from the main actors. The average scoring and synthesis of the results were performed after the first round of data collection. This provided the basis for the second round of data collection through the digital questionnaire to identify risk mitigation and contingency actions. Last, the stage "**share"** involved the documentation of results and communication to the main actors.

4. Results

This section is divided into two parts: Section 4.1 provides a description of the digital services, which are an output of the technical activities previously described. Then, Section 4.2 presents the identified risks associated with the implementation and use of the three digital services. The order of the activities aims to address the identified gap in the literature regarding the lack of documentation of risks of digital servitization in context-specific environments.

4.1. Applying servitization and digitalization in the machine tool industry

The three digital services developed are software-based and built through simulation models for processes, machines, and flow optimization, with the main objective of conceptualizing and designing them to align with some of the main sustainability and eco-efficiency objectives [77]: (1) reduce defects, (2) avoid overproduction, and (3) reduce waiting times. The prioritized principles were highlighted in the initial discussions with the project consortium as useful measures to address sustainability problems that could potentially be supported through digital services. The development process of these services involves performance evaluation, with the prospective plan of developing the models into digital twins. The multidisciplinary modelling approach enabled a holistic view to evaluate how a manufacturing system can work towards sustainability goals by interlinking data in the same modelling environment.

The digital services developed and offered to the companies are described in Table 2.

The first digital service focuses on Zero Defect Manufacturing (ZDM), a concept that finds its origin in the long history of simulation of subtractive manufacturing processes. In this digital service, corresponding predictions are utilized for planning, validation, and optimization of CNC machining processes. With the advancements in computational and algorithmic capabilities, the simulation of the coupled machine-process behaviour for complex machining processes and large workpieces is within reach. The output of the process-level forces is used in the machine-level simulation framework, figuratively the virtual machine "feels and senses the process", behaving as if it was in real operation

Table 2
Description of the digital services.

Digital service	Description
Zero Defect Manufacturing (ZDM)	ZDM uses a framework that combines process and machine simulations to help achieve established quality goals of machine tool manufacturers and end-users, optimizing the machining processes. The service is based on a model representing the actuation system of the machine tool drive, which estimates the positioning error of the machine considering the mechanic parameters of the machine, the drive, and the controller. A web-based application was developed for the use of setup engineers. The mechanical parameters to be introduced are the mass of the drive, the mass of the element to be moved, and the stiffness and damping between the moving mass and the drive. The digital service evaluates the trajectory of the controller, considering the dynamic properties of the system. This digital service evaluates many signals in a short time span, rapidly detecting the source of the problem.
First Time Right (FTR)	This digital service is a cost-effective for collision avoidance system (CAS) focusing on small-series and single-part manufacturing. In this context, it is especially relevant to ensure the first produced part is a good part, with minimal effort for setting up and human supervision. By focusing on the first-time right principle, the quality of the workpieces will be increased with support of simulation-based accurate process planning, leading to less resource waste. This digital service is based on a model that uses polygonal meshes generated by a vision system and defines collision areas for the CAS in a machine CNC controller, ensuring first time right production.
Lean Production (LP)	This digital service optimizes production flow connected to the physical assets and simulation tools via an IoT platform. The architecture of this digital service is composed of 1) asset, 2) IoT gateway, 3) digital cloud, 4) modelling tool and 5) optimization tool. One of the objectives of this digital service is to find the best sequence of parts given an initial production plan, composed of certain references and batch size, assuming the setup activities (i.e., jaw chucks, centering, calibration, tools) and time differ, depending on historical references. The functionalities of the solution are visualization of production data, definition and simulation of the production plan, visualization of simulation results and optimization.

mode.

The second digital service, First Time Right (FTR), was developed as an in-process mechanism for those cases where the simulations fail in their attempts to guarantee ergonomics, safety, and efficiency. This digital service aims to combine the advantages of simulation and vision-based approaches in a cost-effective solution for collision avoidance focusing on small-series and single-part manufacturing. FTR can address European machine tool builders' sustainability, competitiveness, and social challenges, by enabling the offerings of more attractive machine tools that require lower operator skills along with reduced risk of damage during machining process and preventing resource waste. Collision evaluation usually consists of incremental steps that incur increasing costs. Identifying or discarding potential collisions through a simple and non-costly early step can reduce the need for high-cost evaluations.

The third digital service, Lean Production (LP), is based on the idea that lean approaches used in the design and operations of manufacturing systems are needed to adopt new digital technologies and face new manufacturing challenges. The aim of this digital service is to provide a simulation tool for production process managers that showcases connected machine tools and production line simulation tools, enabling automatic adjustments in the line simulation model based on the data generated by machines and providing functionalities that improve the management of production lines.

4.2. Risks and challenges of servitization and digitalization in the industrial context

This subsection presents the risks identified by the stakeholders; an output of the EXPLOITT methodology followed and used for the digital services presented as a subject to use the tool for risk identification.

The risks perceived by the stakeholders regarding the three software were divided into nine categories of impact within the organization, related to risks on (a) business, (b) project, (c) strategic, (d) legal, (e) team, (f) technical, (g) integration, (h) quality, and (i) planning, presented in Table 3a.

5. Discussion

This section discusses the development of the digital services as a first step for the identification of applications of servitization and digitalization in the machine tool industry. Further, it reflects on the implications of the risk analysis and compares it to the literature findings.

5.1. Digitalization and servitization as support for the machine tool industry's objectives

The three digital services developed and presented in this study showcase the potential of adopting servitization and digitalization in the machining tool sector. Sustainability, eco-efficiency and circular economy principles were used as an axis for the conceptualization of the digital services, with goals that include: zero defect manufacturing, optimization of machine tool processes, collision avoidance, ensuring first-time right and improving production flows. The potential impact of these digital services is timely, being the automotive sector one of the main stakeholders in these case studies, digital services can help address the material availability crisis at European and global level, benefiting from maximizing the usage of resources and scrap-avoidance.

This study identifies that machine tool companies have become increasingly interested in environmental issues, aiming to limit the amount of scrap and waste production to meet governmental quotas. Machine energy consumption modelling is a pre-requisite for energy saving in manufacturing [53], and in the context of this research, firms expressed that although they do not always adopt the sustainability discourse in their main product or service description, having environmental priorities has been in the raise. Digital technologies in new

Table 3
Risks identified for the digital services.

	Risks identified	Digital services		
		ZDM	FTR	LP
A. Business				
A1	CNC (Computer Numerical Control) systems are not open to integrate the digital services.		x	
A2	Complex to integrate the digital service with existing ERPs (Enterprise Resource planning) and MES (Manufacturing Executing Systems)			x
A3	IT infrastructure of customers is not ready to provide data to suppliers.	x		x
A4	Industrial European crisis, hardships getting industrial supplies from abroad.	x		
A5	Specific simulations need to be developed for each mode, representing high costs	x	x	
A6	Rapid evolution of the process managers creates difficulties to update the systems			x
A7	The success of the digital service relies in maintenance and suppliers' updates		x	
B. Project				
B1	Each machine could require 3D emulators with financially unfeasible costs	x		
B2	Developed process simulators and digital twins could fail to generate improvements	x		
B3	Model validation could require machines running to failure, translating to high costs		x	
B4	Lack of funding for death-valley innovation to market		x	
B5	Lack of safety on data exchange, low latency when connecting with the cloud			x
B6	The information could be difficult to understand and process			x
B7	The production process manager could fail to be tested in complex and real environments (as it must include several references, providers, and production lines)			x
B8	The production process manager could require continuous connectivity to internet, interfering with industrial security and remote locations			x
B9	There could be unavailability of connected machines and lead to lack of data and difficulty in emulating failures	x	x	
C. Strategy				
C1	It could be difficult to integrate with existing production planning tools			x
C2	There could be lack of data to obtain results, precluding development of future models	x	x	x
C3	The digital service can't be tailored for each industrial application, not able to indicate the necessary information			x
C4	New business models and skills are required - might lead to company growth	x	x	
C5	The cost-benefit ratio could be too low	x	x	x
D. Legal				
D1	The partners could fail to discuss all relevant terms of the digital services.	x	x	x
D2	The constant internet connectivity required could imply security risks to the clients			x
D3	Lack of agreement on data ownership leads to no access to data	x	x	x
D4	Open/source software could represent lack of security	x	x	
E. Team				
E1	Lack of skills impedes customizing and adjusting the module	x		
E2	Lack of communication between the manufacturing technician and the IT team could compromise the usability and quality of the results	x	x	
E3	The IT team could be unavailable or located far away the machine location	x		
E4	Lack of availability of highly trained personnel needed for the implementation phase		x	x
F. Technical				
F1	Digital services could create dependence on few suppliers	x		
F2	The IoT structure and data communication could be too complex	x		
F3	The multicamera location could be too complex to be applied in a real warehouse		x	

(*continued on next page*)

Table 3 (*continued*)

Risks identified		Digital services		
		ZDM	FTR	LP
F4	Conflicts installing the multi-camera solution in real manufacturing environments		x	
F5	Features developed and tested under laboratory conditions in the project development, may not work as expected in field given the low connectivity available at times		x	x
F6	The costs of licences and maintenance service could be too high			x
F7	Integration with existing CNC systems could be complex and too costly		x	
F8	Maintenance, repair, and substitution of parts could require too technical and specialized knowledge			x
F9	The digital service could fail to be integrated with other software in production lines	x	x	
G. Integration				
G1	Customer could fail to gather the required data to simulate manufacturing processes	x	x	
G2	Successful cyber-physical communication could require an unavailable degree of reliability and stability of internet connections	x		
G3	The integration of new references and production lines could fail			x
G4	Interoperability issues of production process manager with data bases could arise			x
G5	There could be lack of compatibility with standards i.e., ISO		x	
G6	Module dependencies of the collision avoidance system could fail to be clarified	x	x	
G7	Some industrial processes could fail to be digitalized and available			x
H. Quality				
H1	Low performance capacity limits storage, communication, and availability	x		
H2	Experience and manpower shortages limit implementation of the simulators	x		
H3	Non-exhaustive tests before commercialization limits system robustness	x		
H4	Competitors could develop better quality of collision avoidance systems		x	
H5	Low capacity could fail to ensure same or better quality than current offline systems		x	
H6	Reliability of the solution in the market could be too low		x	x
H7	The periodic updates of the system could be incompatible with the novel systems			x
I. Planning				
I1	Financial disadvantages could be faced if none or only few clients adopt the app	x		
I2	Low data capacity could restrict management of several references or production lines			x
I3	Needed resources to install the production manager could be unavailable	x	x	x
I4	The initial effort cost could be higher that the benefit	x	x	

manufacturing processes will soon become not only a nice-to-have, but a complete necessity to achieve productivity, efficiency, and sustainability goals [43], when selecting companies for this study it was clear that they believed in the potential of exploring the increased use of digitalization in their production processes, and they expressed that most of the times they did not know which problem to address first. This way, the advantages of servitization be able to justify its adoption, beyond the economic feasibility if fair trade-offs can be demonstrated [26]. This becomes highly relevant as the companies are often hesitant about their customers' willingness to incur in increased costs by adopting additional services, particularly if they could not demonstrate sufficiently the potential of the digital services. To do so, quantitative assessments i.e., LCC (Life Cycle Costing) are suggested as they can help advance the understanding of the feasibility of individual cases.

The exploratory nature of this research work, which matches the emerging nature of the field of literature focusing on the intersection between the concepts of servitization, digitalization and sustainability in the machine tool sector [3], provides benefits from tightly-defined and specific industrial cases. This can support manufacturers by providing insights to re-examine and re-construct their priorities before undergoing large-scale. Also, developing trust and partnerships can require long time investments and alignment of qualitative priorities [80] before implementation processes of new elements in day-to-day operations.

Exploring such areas of opportunity could support envisioning a future where services play an even larger role in manufacturing activities. In the future we could see an increase in models that bring increased elements of servitization to manufacturing, where value is found in the principles of shared economy, servitizing sustainability. The already appearing "pay-per-stress", paves the way for exploring more service-based offerings in this industrial context [61], and can support towards a firm to achieve sustainability is delivered and the main responsibility lies in a third partner. However, these models could require to develop strategies that deal with risks related to responsibility-transfer [71].

This study is not one without limitations. There is still room for studies that explore more industrial needs and address them through a larger range of digital services, include more industrial experts and more companies from diverse geographical locations and industrial sectors, and that quantitatively assess the compatibility and transferability of data and the communication between stakeholders of one or several companies.

5.2. Risks associated with digital servitization in the machine tool industry

The machine tool industry is a large supplier of pieces for many products of several actors in the manufacturing industry and severe potential errors could be solved through good communication. The highest-rated risk among the ones considered **unacceptable** by the industrial practitioners was identified in the legal category, posing the concern of having the partners fail to discuss all relevant terms of the digital service. Data sharing across a complete supply and value chain is often required, and complete product lines could be disrupted if the partners have not dedicated the required time and efforts to agree on mutual objectives and business models [65,81].

Good communication and trust-based relationships between stakeholders have become increasingly relevant, as resilient value chains are urgent and not yet achieved in the manufacturing industry. Many global organizations have addressed the post-pandemic manufacturing industry as vulnerable, facing the need for additional tools to avoid disruptions upstream and downstream [82].

Further, the category considered **high** included risks from six out of the nine categories presented in the results, including business, project, strategy, legal, team and technical. From the business category, the major concerns relate to integrating the digital services with the currently existing ERPs and MES (risk A2). Most firms experience that it could take months or years for ERP systems to be fully integrated, delaying the realization of benefits, and limiting their acceptance across organizations [83]. Also, the expected results could be compromised due to the unavailability of connected machines and the potential lack of data and hardships when emulating failures (risk B9).

Further, having several industrial sectors in one value chain could represent a risk, as there is no understanding yet of whether digital services can be adapted for each actor, which could mean a lack of necessary output data (risk C3) and it is important to address the lack of available data and the top-down approach that involves the design of service-added offerings as it could lead to an underestimation of the price required to make services profitable [84].

The results of this study show the need for future research where quantitative methods explore the economic feasibility of new business case adoption with risk-sharing strategies in place. Economic feasibility is particularly relevant as companies expressed concerns about the implementation of the services incurring more costs than the regular manufacturing process, meaning all the expenditures involved do not always justify business model transitions (risk C5). Further, data ownership agreements need to be discussed to avoid problems induced by sharing industrial partners' data (risk D3). Literature addresses this risk by bringing light to how "trust-less trust" must become an element in servitized machine tool industry [85,86]. In this way, technology allows trust in the outputs of the digital system regardless of the capability of stakeholders to trust each, requiring manufacturers to react responsively to transitioning business models [87].

The lack of available talent caused partly by the reshuffling of the workforce through the recent global pandemic show effects which are not yet final, creating concerns about the lack of availability of highly trained personnel to perform technical installations (risk E4). In recent literature, Sassanelli et al. [88] found concerns about skills shortages for data analysis and the lack of know-how regarding modelling, data analytics and machine learning algorithms, suggesting the involvement of human resources in recruitment and upskilling activities.

The technical risk category (F) included four of the risks considered high. Namely, (risk F3) the multicamera location required in the digital services could be too complex to be applied in a real warehouse, (risk F3) facing installation problems could mean that features developed and tested under laboratory conditions do not perform as expected given occasional low connectivity availability (risk F4) [81]. Also, unaccounted-for costs of licences and maintenance services could be too high (risk F6), as regardless of the attempts to showcase the potential sustainability advantages of digital services, companies mostly develop increased motivation when financial advantages are part of future scenarios. Some servitization efforts are never concluded when new services are included in the product portfolio and therefore to a company's costs due to poor planning [89,90], bringing light to the sense of urgency towards developing methodologies that allow planning in a timely manner.

5.3. Recommendations based on the risk analysis

The risks identified, most specifically those that were considered of potential unacceptable and of high impact, as presented in Fig. 2, were further discussed with the industrial experts and researchers to create a list of activities that could be performed both to mitigate or prevent the risks. These activities are described in Table 4.

While the questions posed in this research work are answered in a case-specific manner and the authors do not claim complete generalizability, the validity of many of these expressions can be supported by similar observations in comparable or tangential studies.

To address the **unacceptable** risk regarding the lack of understanding of the terms of the digital service among the partners, some actions are recommended which include create joint-ownership agreement between partners, with accurate definitions of the results produced by each of the actors and explicitly describe the conditions of ownership of the data. Also, define IP strategies for how the results and data outputs will be protected, define frequent meetings to re-evaluate the agreed conditions, and define penalty fees in case the agreements are broken.

Then, to address the risks considered **high** some strategies are also suggested. To deal with concerns about integration with currently existing ERPs and MES, the suggestion is to evaluate data formats, develop audits about documentation and assess matches and standards of interoperability at all the stakeholders' facilities, as well as establishing closer relationships with the ERP and MES software providers to push towards interconnectivity and standardization, enabling the forecasting of future disruptions. Further, it is important to evaluate the simplicity of the implementation and start with small wins, avoiding disruptions in the most critical part of the systems.

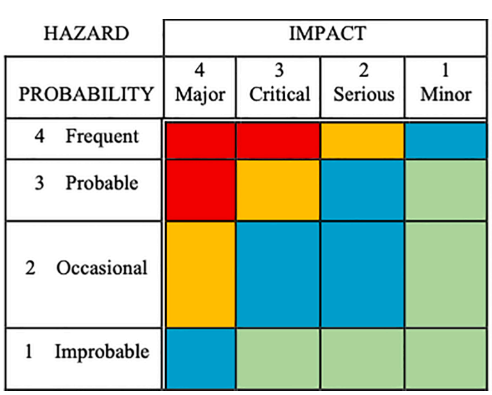
5.4. Theoretical and managerial implications

From a theoretical perspective, this study showcases the gathering of industrial expertise by following qualitative research methods that support the classification of risks on digitalization and servitization in the machine tool industry. The research work identified a lack of case studies that document the risks associated with specific digital services in relation to connected value chains. Although the generalizability of the results is a complex statement, the risks identified and classified in this study can be transferrable to similar digital services that require high availability of technical skills, trust relationships among stakeholders and a clear definition of shared responsibilities for new business model design.

From a managerial perspective, the results of this study contribute to the identification of potential risks which can be helpful when designing and defining new business models within the machine tool industry. An understanding of commonly perceived risks which are also reflected in literature brings value to manufacturers and other companies in a value chain to understand what situations must be fool-proofed and co-create solutions to avoid shifting problems from one life cycle stage to another. Further, this study provides a list of possible mitigation activities which can enlighten manufacturers to not only focus on situations that could not go according to plan, but also by equipping them with ideas of how to address such risks through mitigation and contingency activities.

6. Conclusion

In the era of Industry 4.0, it is important to explore the potential of digitalization and servitization in the manufacturing industry, particularly in the machine tool sector. This paper describes a case study where three digital services were developed and proposed to machine tool experts. Several risks associated with the adoption of digital servitization in the machine tool sector were identified. The most prominent risks found by this study were: lack of agreement between partners on the conditions for new digital services; lack of interoperability between the digital service and pre-existing software installed in the machines; lack



Code	Risks
Unacceptable	D1
High	A2, B9, C3, C5, D3, E4, F3, F4, F5, F6
Medium	A1, A3, A7, B1, B2, B5, B6, B7, B8, C1, C2, C4, D2, E1, E2, F1, F2, G1, G3, H2, H3, H4, H5, H6, H7, I1, I2, I3
Low	A4, A5, A6, B3, B4, D4, E3, F7, F8, G2, G4, G5, G6, G7, H1, I4

Fig. 2. Risk matrix.

Table 4
Risk responses - mitigation and contingency activities.

Category	Mitigation	Contingency
A. Business	Ensure accessibility and criticality of data Develop step-by-step process instructions Map the pre-required IT infrastructure Support partners in updates and adjustments of IT infrastructures Communicate and collaborate with ERP and MES software providers Collaborate with standardization organizations. Calculate and show costs estimations (include digital service investments and IT updates)	Develop follow-up strategies to evaluate functionality Create hazards testing processes Integrate different proposals in services portfolio
B. Project	Develop preliminary data sets with extensive empiric data in testing phase and request evaluations Arrange access to machines located at research centres and technology providers to gathering data that simulates industrial reality	Include skilled research centres in the characterization of machine tools Use of public data sets
C. Strategy	Evaluate reality and representativeness of data. Internally audit the testing processes. OTA testing (assess connectivity and stability) with open data sets Review, consider and update risk documentation Define post-implementation follow-ups	Offer maintenance services
D. Legal	Highlight win-win situations in negotiation processes Agree on delimited datasets Implement NDA or ownership agreements for data sharing Propose penalty fees for breaches of contracts Implement smart-contracts and block-chain approaches to ensure security and trustability Local implementation on clients' facilities	Anonymize data Take legal actions based on the NDA or data ownership agreement Rely on legal consultancy Offer to reimburse financially the data provided
E. Team	Provide training services at customers facilities Prioritize trainings for new employees Personalize the outputs through clear visuals Collaborate during implementation with customers' maintenance team Identify potential maintenance services that can be offered to the clients Provide support through a hotline	Offer training sessions to the new members of the team or when updates to the digital service occur
F. Technical	Analyze configurations of manufacturing environments and provide diverse options Involve maintenance managers in technology investment decisions and implementation Follow-ups to identify and implement potential improvements Create attractive offers to potential customers, offering economic and functional advantages to encourage early adopters	Provide maintenance services adjusting the implementation of the hardware/software as required Adjust the algorithms, sensors or cameras as needed Update the step-by-step process for implementation with the impacts and solutions given in new implementation processes
G. Integration	Before the implementation ensure correct data formats, audit documentation, interoperability matches, and standards applied at clients' facilities	Try to implement a step-by-step based approach, starting from the easiest equipment to be integrated or the less critical from the point of view of resource assignment

of available connectivity and dataflow; low cost-benefit ratio; concerns on data ownership; and a lack of transferability of simulations to real industrial environments. The identified risks were categorized based on levels of impact on the company, which are of different magnitudes considering that the involved companies have different sizes, capabilities, and yearly revenues.

The most important mitigation and contingency activities included: assess connectivity and stability with open data sets; establish communication and collaboration with ERP and MES software providers; calculate and show cost estimations across complete lifecycles; implement NDAs and data-ownership agreements and perform frequent follow-ups.

6.1. Research limitations

This study experienced some limitations which can highlight the next research steps that could contribute to further covering the identified research gap.

- This study finds a limitation in the number of digital services developed and the timeline in which this analysis is performed, which is mainly at the beginning-of-life cycle stage. This can be seen from two perspectives, on the one hand, beginning-of-life cycle stage is the most influential when it comes to planning business models, particularly with sustainability agendas in mind. On the other hand, an analysis how risks express and materialize in later lifecycle stages could provide interesting results.
- The number of companies involved is limited to three firms, which allows an in-depth analysis of their perceptions of risks. The fact that the companies are of different sizes provides valid points to firms' reactions towards similar risks regardless of their size but limits generalizability.

6.2. Recommendations for future research

Future research is suggested to address more of the eco-efficiency and sustainability principles, capturing more sustainable value from unexplored research avenues. Also, the exploration of the implementation stage can materialize further the results. Last, the analysis of how the mitigation and contingency actions impact the process of the firm can provide valuable research insights to academics and practitioners.

In conclusion, this study contributes to bridging the gap between theory and practice by identifying risks and mitigation activities, providing insights from empirical cases and insights from real industrial contexts.

CRediT authorship contribution statement

Clarissa A. González Chávez: Conceptualization, Methodology, Visualization, Formal analysis, Investigation, Validation, Writing – original draft, Writing – review & editing. **Gorka Unamuno:** Conceptualization, Methodology, Data curation, Writing – original draft. **Mélanie Despeisse:** Conceptualization, Methodology, Supervision, Visualization, Validation, Writing – review & editing. **Björn Johansson:** Writing – review & editing, Supervision, Project administration, Funding acquisition. **David Romero:** Conceptualization, Writing – original draft. **Johan Stahre:** Conceptualization, Writing – original draft, Funding acquisition.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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