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Challenges of achieving digital transformation in manufacturing firms: the case of predictive maintenance and spare part inventory management

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Abstract

Purpose
Predictive maintenance (PdM) has attracted increasing attention in recent years owing to the emergence of advanced condition-monitoring technologies and data analytics tools. However, the application of PdM in spare parts inventory management across the Supply Chain (SC) has not been sufficiently investigated and its Digital Transformation (DT) requirements have not been adequately researched. Therefore, this study aims to analyse the organisational readiness for the use of integrated spare parts inventory management together with PdM systems across the SC.

Design/methodology/approach
A series of semi-structured interviews were designed and took place across organisations in various industries to address the pre-defined research aim. In total, 15 interviewees were recruited through purposive sampling, including managers and technicians in various organisations from different industries.

Findings
The findings reveal that while maintenance planning and optimisation has been the subject of extensive research for decades, manufacturers are still encountering barriers in adopting and implementing digital innovations. The experts also highlighted the need for an integrated Information System (IS) enabling data sharing across the organisation since lack of integration has a vital impact on the overall business and operations performance as well as the successful DT of the enterprise. In addition, they report that the necessary and relevant data for implementing PdM is not captured or stored in their organisations.

Originality
The present study emphasises the technical, organisational, and environmental (TOE) dimensions that can affect such DT, and sheds light on the enablers and inhibitors that organisations face in their efforts to be technologically ready to embrace the digital integration of PdM with spare part inventory management. It is recommended that a clear shift in management mindset and organisational culture is necessary for companies to realise the benefits of PdM and the DT that will result from its implementation.

Keywords: *digital transformation, predictive maintenance, spare parts, inventory management, supply chain, technology readiness*

Quick Value Overview

Interesting because:
This study explores the readiness of manufacturing companies to digitalise their spare parts inventory systems through integration with Predictive Maintenance (PdM). Previous research primarily focuses on the technical aspects of PdM, while this paper delves into the market readiness and demand as well as the sociotechnical challenges that companies face during such Digital Transformations (DT). We consider both the technological organisational and environmental factors necessary for the successful integration of a PdM system, providing a comprehensive understanding of the barriers and enablers in the digitalisation process.

Theoretical value:
Our study contributes to theory by revealing critical relationships between digital readiness and the adoption of PdM in the spare parts inventory management area. Our findings challenge the prevailing assumption that technological readiness alone is sufficient for DT. Thus, highlighting the importance of sociotechnical dynamics, offering new insights into the existing theoretical framework on digitalisation in manufacturing.

Practical value:
Our research provides actionable insights into the strategic planning required to overcome barriers to PdM integration. It suggests that managers should prioritise the development of a digital strategy that aligns with the organisation's culture and addresses resistance to change. The findings show that by focusing on both technological, organisational and environmental factors, manufacturing firms can create a conducive environment for successful DT.

1. Introduction

Digital transformation research is growing and theorising how digital innovations can be implemented in organisations is an area that has immense potentials (Verhoef *et al.*, 2021). DT is considered the process of using digital technologies to fundamentally change how an organisation operates and deliver value to its customers and employees. This can be the adoption of new technologies such as Artificial Intelligence (AI), Internet of Things (IoT) and systems that can improve efficiency, reduce costs, encouraging innovation and increasing revenue (Brodeur *et al.*, 2023). Organisations are increasingly investing in DT which enable them to better support the exchange of expert knowledge and accelerate innovation in various business areas (Eden *et al.*, 2019).

Maintenance is one of these business areas and it is considered a critical operation in the manufacturing industry while availability, reliability, and maintainability are basic requirements for manufacturing machines, although component and equipment failures are inevitable and happen occasionally (Karuppiah *et al.*, 2021). Traditional maintenance aims to restore a system to its functional condition after a failure occurs, however, this approach tends to be inefficient in today's competitive business environment because it relies on the assumption that spare parts are always available, which is usually not the case in practice (Silvestri *et al.*, 2020). Thus, with the increasing requirements for the availability and reliability of digital systems, conventional maintenance approaches are becoming obsolete and even less effective. It is essential for organisations to acquire the necessary data within their systems to ensure that they interconnect and monitor the condition of their assets in real-time. This, in turn, allows them to effectively plan their maintenance activities and manage the inventory of spare parts, thereby reducing machine downtime (Tortorella *et al.*, 2022).

PdM enables more effective spare parts inventory management across the SC, while it can identify different spare parts demand patterns and accurately forecast the demand based on the analysis of the collected data (Pinçe *et al.*, 2021; Hu *et al.*, 2018). Milojevic and Nassah (2018) found that 93% of companies rate their existing maintenance activities as inefficient, mainly due to the occurrence of unplanned downtime and sudden failures, and they are considering the opportunity to adopt PdM systems to improve their spare part inventory management. For this purpose, empirical evidence is necessary to evaluate the feasibility of integrating PdM with spare parts inventory management (Selcuk, 2017), and identify organisational barriers in the way that these technological solutions are adopted. Meanwhile, the DT required for a successful implementation of PdM systems, encompasses concerns for companies since they often struggle with redesigning their organisational business models in an effort to achieve the required business performance enhancements (Rahmati *et al.*, 2020). Organisations cannot ignore the challenges that are associated with DT since such digital changes transform business processes and have an impact on employees and customers (Eden *et al.*, 2019).

In the past decade, technological advances have had a great influence on how companies maintained their equipment while maintenance activities have been revolutionised by technological innovations such as new devices and techniques for condition monitoring and asset inspections (Tortorella *et al.*, 2022). Although PdM is crucial for preventing unexpected shutdowns (i.e., unplanned downtimes), its capacity and role in the manufacturing landscape has not been adequately acknowledged (Dalzochio *et al.* 2020). The potential of PdM systems that can offer advanced capabilities for maintenance management, are still neglected within the manufacturing sector (Zhang *et al.*, 2021). Therefore, the primary aim of this research is to analyse the capacity and readiness of manufacturing companies to adopt a digital solution comprising a PdM system with spare-part inventory management. The focus is on the challenges that companies face in their efforts in integrating PdM with their spare parts inventory and enabling the desired DT across their SC.

We focus on the technical, organisational, and environmental (TOE) dimensions that can affect such a digital system. The TOE framework is widely adopted in scientific inquiries to comprehend how businesses come to embrace numerous types of innovations (Nguyen *et al.,* 2022; Chatterjee *et al.*, 2021; Aboelmaged, 2014). Thus, the following research question will be explored:

What are the major enablers and inhibitors for organisations embracing the digital transformation as a result of integrating PdM with spare part inventory management?

The remainder of this paper is organised as follows. Section 2 discusses PdM and spare parts management, DT in organisations while outlines the research framework. Section 3 describes the methodology of the proposed study. Section 4 presents and discusses the findings of the research. Section 5 provides concluding remarks, managerial implications, and suggestions for future inquiries.

2. Literature review

2.1 PdM and Spare Parts Management

Traditional maintenance approaches, such as preventative maintenance, primarily rely on the experience of operations (e.g., maintenance and asset) managers to diagnose or reduce failures (Karuppiah *et al.*, 2021). Such a strategy is prone to inaccurate forecasts and tends to over-maintain assets, which results in tied-up capital (Errandonea *et al.*, 2020). The lack of spare parts can lead to unplanned machine downtimes and impose additional costs on manufacturers (Usuga-Cadavid *et al.*, 2021). Depending on the type of products, maintenance expenses can range from 15 to 70 percent of the total production costs (Rahmati *et al.*, 2020). Hu *et al.* (2018) highlighted further that any spare parts management strategy should enable companies to determine the type of spare parts, ordering times, and their optimal quantity. They recommend that companies need to maximise the availability of spare parts and minimise the economic costs that mainly involve inventory holding and stock-out penalty costs (Hu *et al.*, 2018). In this sense, forecasting the demand for spare parts is a key but challenging aspect of spare parts management due to profound uncertainties (Pinçe *et al.*, 2021). Zhang *et al.* (2021) acknowledged that most studies in the spare parts inventory management literature only focus on inventory problems, and they do not investigate the advantages that companies can gain from strengthening the interconnectivity between spare part inventory management and maintenance.

PdM is a prognosis maintenance strategy that utilises collected data from assets to predict the type and time of maintenance, resulting in no or very limited downtimes (Errandonea *et al.*, 2020). The PdM is a maintenance strategy that detects early anomalies in equipment behaviour and predicts potential future failure modes based on a vast amount of historical and real-time data (Karippur *et al.*, 2024). The optimisation of PdM processes can have a significant impact on spare parts inventory management, especially for improving the Overall Equipment Effectiveness (OEE) and reducing lead times within the SC (Cui *et al.*, 2021; and Nurprihatin *et al.*, 2019). Lead times can be reduced by planning the required maintenance ahead of breakdowns and ensuring the availability of the required spare parts (HassankhaniDolatabadi and Budinska, 2021). Additionally, PdM can help companies maximise in-service equipment lifetime and cut operation and maintenance costs (Selcuk, 2017), particularly when related maintenance data are available (Usuga-Cadavid *et al.*, 2021).

PdM is considered as one of the most effective ways of maintenance that has the ability to minimise equipment failure rates and reduce the maintenance costs (Çinar *et al.*, 2020). Therefore, PdM will have direct value on manufacturing productivity through improving the OEE as one of the Total Productive Maintenance (TPM) metrics (Nurprihatin *et al.*, 2019). Chiarini (2015) argues that poor OEE will result in higher manufacturing cost due to higher work-in-process and increased lead time while improved PdM in the manufacturing SC can enhance overall manufacturing productivity.

Despite the fact that PdM is a rather effective way to improve efficiency and effectiveness across the SC, yet, according to a PricewaterhouseCoopers survey, only 11% of the companies surveyed have adopted PdM solutions (Çinar *et al.*, 2020). PdM is considered to be a new area of research and thus there is an interest in exploring how it is used and implemented across the SC (Çinar *et al.*, 2020).

Despite the advantages gained through the integration of PdM with SC systems, the literature outlines several complexities that often hinder companies' efforts (Dalzochio *et al.*, 2020). Some of the reported challenges in implementing PdM include data security and privacy issues, availability of sufficient historical and real-time data, legacy systems, lack of expertise, investment costs, increased upfront infrastructure setup, and complexity of the system (Tortorella *et al.*, 2022; Cui *et al.*, 2021). Giada and Rosella (2021) found that empirical research addressing the field of spare parts inventory management integration is scarce. To reduce this gap, this research was designed to understand the barriers that can hinder the integration of PdM across the SC.

2.2 Digital Transformation in Organisations

Digital platforms have accelerated the development of unprecedented types of business-to-business (B2B) transactions, along with more complex and configurational models for business-consumer relationships (Brodeur *et al.*, 2023). More specifically, DT is related to the implementation of technologies, and it can influence productivity, value creation, and social welfare (Tortorella *et al.*, 2022). Its consequences include changes in the business processes of an organisation, while it can advance SC operations and modify business models, including digitalisation processes, with a focus on a business's digital efficiency (Wang *et al.*, 2024). Verhoef *et al.* (2021) argue that since DT is multidisciplinary by nature, organisations need to be in a position to recognise and deal with changes across their strategy, marketing and SC. Digital technologies can affect a company's structure, reshape organisational culture, and optimise logistic costs across SC (Brodeur *et al.*, 2023).

DT nowadays is used broadly in various industries, and it can lead to failure because of the complexities and the challenges it involves (Hartl 2019). Hartl (2019) discussed that during DT organisations need to consider not only the changes that take place from a technological perspective, but also take into account the impact that digital systems have on organisational and environmental aspects surrounding a business (Wang *et al.*, 2024). DTs often fail or meet strong resistance because there are no appropriate management processes in place or there is lack of clear leadership for guiding the change. Some of the main issues that occur during DT are data security challenges, lack of interoperability with existing technologies, lack of control over suppliers and resistance of employees (Eden *et al.*, 2019).

Ghobakhloo and Iranmanesh, (2021) point out that industry reports show that although the manufacturing sector had an early lead in DT and automation of their internal processes when it comes to achieving DT through the implementation of smart manufacturing, they are lagging. Smart manufacturing can be utilised for improving SC processes through data analytics by adopting digitalisation and integration of business partners into value networks (Tortorella *et al.*, 2022). This integration can enable organisations to monitor production equipment effectively and detect early signs of components or machine breakdowns. These signs may be detected by data exchange and analytical tools that can be deployed throughout the production processes from procurement to final product delivery, and most importantly, maintenance (Carvalho *et al.*, 2019). However, more research is needed in order to understand such changes and encourage companies to undergo the desired DT by integrating PdM and their spare parts systems. It is equally important for organisations to realise that DT can disturb usual business models and businesses should invest in measures for adoption of DT such as profits, productivity and competitiveness (Llopis-Albert *et al.*, 2021).

The increasing adoption of digital technologies in manufacturing industries has led to the emergence of Industry 4.0 (I4.0) (Zheng *et al.*, 2020) and technologies such as AI, IoT and big data. These technologies have the potential to revolutionise manufacturing processes, improve productivity, and enhance competitiveness. One of the critical applications of I4.0 is in PdM, which involves the use of data analytics to predict equipment failures and schedule maintenance activities while it can reduce downtime, increase productivity, and lower maintenance costs (Karippur *et al.*, 2024). More specifically, the integration of I4.0 and PdM has significant implications for manufacturing technology management. For instance, the adoption of I4.0 technologies can enable PdM to move from a reactive to a proactive approach, where maintenance activities are scheduled based on predicted failures rather than scheduled intervals (Tortorella *et al.*, 2022; Karippur *et al.*,2024). This approach can lead to significant cost savings and productivity improvements. Furthermore, the integration of I4.0 and PdM can enable the development of new business models since, manufacturers can offer PdM as a service, where they provide maintenance services to customers based on real-time data analytics (Tortella *et al.*, 2022). This business model can lead to new revenue streams and improve customer satisfaction. However, to realise the benefits of I4.0 and PdM integration, manufacturers require significant investment in infrastructure and skills development while such a complex integration requires collaboration between different functional areas, such as operations, IT, and maintenance (Zheng *et al.*, 2020).

How organisations can minimise the disruptive nature of DT can depend on the type of company, the geographical location that the company operates in, the skills and engagement of their employees while training and education in the organisations can be some of the determinants that can be crucial in the adoption of digital innovations (Ghobakhloo and Iranmanesh, 2021). Therefore, as digital innovations are active across different industries and they break down the old, traditional borders and restrictions between companies, it is important to study how organisations, individuals, industries, communities and dynamic sociotechnical systems are interacting and collaborating at different levels and settings. More specifically, digital innovations are seen as a transdisciplinary topic (Llopis-Albert *et al.*, 2021), and thus, more efforts need to be made to gain an in-depth understanding of the digital innovations consequences both as a holistic system across individual employees, companies and industries as well as a broader sociotechnical phenomenon. Thus, this research will focus in exploring the TOE factors that influence technological readiness for DT through integration of spare part inventory management and PdM across the SC.

2.3 Research Framework

Gurbaxani and Dunkle (2019) argue that since DT requires broad reinvention, a useful framework exploring the requirements for digital change must incorporate technological, organisational, human capital, and strategic considerations. Tiddens *et al.* (2022) point out that while the technological aspects of such complex integrations need to be considered it is equally vital to understand and investigate organisational as well as economic aspects relevant to these system implementations. Thus, we have taken the TOE framework that encompasses technological, organisational and environmental elements as the main factors that influence the adoption and implementation of technological innovations by firms and we incorporated the elements of technological readiness as defined by Parasuraman (2000).

Parasuraman (2000) discussed that technological readiness is an individual's or an organisation's ability to embrace new technologies in their efforts to achieve their targets and goals. He identified four dimensions namely optimism, innovativeness, discomfort and insecurity which he used in order to gain a better appreciation of how technological advancements are treated by individuals and organisations. Optimism and innovativeness were considered enablers of the potential technological readiness, while discomfort and insecurity were seen as inhibitors. Optimism demonstrates a supportive belief and attitude towards technology and innovativeness determines an individual's and organisation's positive intention to adapt and accept new things. In the opposite spectrum we have insecurity which refers to the distrust of technology and suggests uncertainty while discomfort highlights the lack of support towards the new technology and suggests an attitude of resistance.

Our research aims to pinpoint the enablers and inhibitors for embracing the digital integration of PdM with spare part inventory management and the DT such endeavours will bring. Therefore, a model that integrates the TOE framework as well as the Technology readiness approach allows us to gain a comprehensive view of these enablers and inhibitors from different perspectives (Golightly *et al.*, 2018; Chatterjee *et al.*, 2021). In doing so we have integrated the TOE framework which is flexible and has been adopted in various domains related to the analysis of readiness, innovation, and technology adoption (Nguyen *et al.* 2022; Aboelmaged, 2014) with the technological readiness approach. Thus, Figure 1 shows an integrated model of TOE and Technology Readiness.

Figure 1: integrated model of TOE and Technology Readiness

PLEASE INSERT FIGURE 1

Some studies have already touched on a few hurdles in the design and operationalisation of an integrated PdM plan (Golightly *et al.*, 2018; Karuppiah *et al.*, 2021). However, the implementation of PdM has not been sufficiently studied, particularly in relation to inventory management of spare parts (Dalzochio *et al.*, 2020). Karuppiah *et al.* (2021) recommended that exploring such integration should involve technical, economical, organisational and social dimensions, as the extant literature typically focuses only on the technical or the economic perspectives. Therefore, the present study intends to identify the key factors that affect the embracement of the digital alignment of PdM and spare part inventory management across the SC.

3. Methodology

Understanding spare parts management across the SC is imperative for organisations in their efforts to be more efficient and effective. Therefore, interpretivism is congruent with a social constructionist approach, and Easterby-Smith *et al.* (2002) state that a social constructionist should interpret the views and experiences of the individuals be able to understand, analyse and construct meaning from them. Thus, the researchers have concentrated on the interpretations and in-depth analysis of the different individuals involved in understanding the implementation of the PdM and a spare parts inventory management system.

While qualitative data is more frequently found in social sciences, it can be very useful to derive solutions from seemingly technical challenges (Billups, 2021). Walsham (2006) argues that interpretive research has become more important in studies that aim to understand digital innovations than it was in the early 1990s when it represented a very small proportion of the technological innovations' literature.

Motivated by the aforementioned work, a series of semi-structured interviews were designed and took place across organisations in various industries to address the pre-defined research aim. In total, 15 interviewees were recruited through purposive sampling, including managers and technicians in various organisations from different industries (see Table I).

Table I: Experts details

Participant	Position	Field
P1	CTO	Software
P2	CEO	Consultancy
P3	Head of Data	Consultancy
P4	Founding Director	Consultancy
P5	General Manager	Manufacturing
P6	Director	Consultancy
P7	Senior Controller (Engineer)	Manufacturing
P8	Senior Lead for SC	Manufacturing
P9	Senior Controls Engineer	Manufacturing
P10	Equipment Support Manager	Manufacturing
P11	Maintenance Shift Leader	Manufacturing
P12	Reliability Manager	Food Manufacturing
P13	Principal Manufacturing Support Engineer	Manufacturing
P14	Director	Consultancy and Products Supplier
P15	Director	Manufacturing

These companies were chosen because they are either in the process of exploring the integration of PdM and spare parts inventory or they have experience in such complex digital innovations. Therefore, looking into these organisations enabled us to understand their readiness and intention to embrace PdM and the DT that derives from such complex technologies. In this research, data saturation (Brinkmann and Kvale, 2015) was achieved at interview 10, since the experts came from similar and related industries (i.e., manufacturing) and they were questioned on the same topic area. Another five interviews were conducted to reach a total of 15 interviews to validate the results and ensure that the interpretations are in line with the rest of the data gathered (Kuzel, 1999).

The interview questions were developed, revised, and refined in an iterative manner through a pilot study as well as through interviews with experts as we were progressing. After completion of data collection and transcription processes, template analysis (King *et al.* 2018) as a form of thematic analysis was used to analyse and interpret the rich and in-depth accounts of the interviewed organisational experts. While the interviews were transcribed for the purpose of analysis, the coding phase was initiated according to the theoretical concepts suggested by the data rather than those imposed by the researchers (King *et al*. 2018). It is important to realise that these initial themes represented only a starting point in the process of analysis, with understanding developed iteratively in response to the data. Organising the raw data into categories was an effective approach to identifying themes and linkages between them. The themes were then studied with the intention of achieving the aim of the research, which is an essential part of qualitative research. For this study, coding was done by extracting keywords and phrases from interviews and sorting them into labelled categories for the themes they addressed or described. The following section presents and discusses the findings of this study.

4. Results

The main aim of our study is to understand the digital integration of spare parts inventory management and PdM. Our findings are presented below, and the structure is based on Figure 2 which derived from data analysis with an intention to gain an understanding of the current practices that companies use, as well as their intention and readiness to invest in the integration of PdM and spare parts inventory management. The findings were classified based on the integration of the TOE framework and the technological readiness approach while the main aspects were discussed and organised by the experts from an enabler/inhibitor perspective regarding spare parts inventory management integration with PdM.

Figure 2: Embracing digital integration of Spare Parts Inventory Management (SPIM) and PdM

PLEASE INSERT FIGURE 2

4.1. Organisational Intention to Invest into a PdM system

Most manufacturers follow a reactive maintenance strategy, which often results in machinery failures and downtimes during production. Therefore, Table II summarises the stages in which each of the interviewed companies implemented their PdM DT. Most of the experts do not have any digital integration in place between their spare parts inventory management and PdM, while those that have some integration in place focus mainly on monitoring the condition of their equipment but have not yet achieved full integration across the SC. Manufacturers claim that they are intending to invest in DT, which will enable them to shift towards a more proactive maintenance of their spare parts; nevertheless, they lack the ability to successfully implement these systems. As one of the experts mentioned, *"it is costly to hold parts for a long time that we will not use. But also, it is a problem if we do not have the parts when we need them…"* (P1).

Table II: Organisational analysis of intention to implement PdM

Experts	P1	P2	P3	P4	P5	P6	P7	P8	P9	P10	P11	P12	P13	P14	P15
Already Implemented integrated digital spare part inventory management and PdM practice	No	No	No	No	No	No	Partly Conditioned-Monitoring (very small scale)	Partly Conditioned-Monitoring (very small scale)	Partly Conditioned-Monitoring (very small scale)	No	Partly Conditioned-Monitoring (very small scale)	Partly Conditioned-Monitoring (very small scale)	Partly Conditioned-Monitoring (very small scale)	No	No
Intending to Implement - Level of Intention	Yes, High	Yes, High	Yes, High	Yes, High	Yes, High	Yes, High	Yes, High	Yes, High	Yes, High	Yes, High	Yes, High	Yes, High	Yes, High	Yes, High	Yes, High
Maturity Level	None	None	None	None	None	None	Very Limited	Very Limited	Very Limited	None	Very Limited	Very Limited	Very Limited	None	None

When the experts were asked what would enable them to achieve the DT through PdM across their SC, most of them highlighted the need for cultural and strategic change in order for manufacturing companies to be more data-driven (P1, P3, P5, P7, P9, P10, P14, P15). They argued that this will enable them to analyse the data available to them, and consequently add more value to their customers and employees. Machine learning techniques can also help manufacturers implement a PdM system effectively, while simultaneously, improving their forecasting. *"We need to have an integrated system with our suppliers for managing the spare parts, this will allow a quick response and better parts management in our warehouses. Imagine how many employees are needed to review/audit 10,000 parts"* (P3).

4.2. Digital transformation through the integration of PdM and Spare Parts Inventory Management

The shift towards the PdM of spare parts inventory management enables manufacturers to compete globally, while empowering them to align their business strategies with the effectiveness of their operations by achieving highly digitalised processes across their SC. Three main inter-connected considerations were surfaced during data analysis and organisations need to investigate them before implementing PdM systems. They tend to consider the financial requirements for implementing such complex systems while trying to balance the benefits that such systems will bring for the business and the challenges that they will need to face. For example, P2 argued that "*it is important for us to assess the financial benefits from such systems, as we are not sure that there is clear proof yet that such digital systems will provide return on investment*".

However, most of the experts did recognise the organisational benefits that they expect to gain from such DT i.e. "*PdM can massively help us to reduce the maintenance and operational costs and ensure the safety of our equipment*" (P8). At the same time though, the same experts are aware of the challenges that they will have to tackle to fully embrace the benefits of such implementations "*Managing the change, people accepting the change and convincing them that this is the future is a main challenge.*" (P13). This is an important finding that we further discuss in the discussion section.

Technological insecurity and discomfort

Many manufacturers still use spreadsheets to manage their spare parts inventories (P9 and P10). The ones that use computerised software have very limited capabilities while these maintenance technologies are not integrated with any other available system across the SC. Companies argue that lack of time and availability of accurate data are two reasons that prevent them from implementing PdM. *"There is lack of the needed information to implement the system, since we do not collect the required data, we do not have an advanced maintenance software to capture such data in an accurate and timely manner"* (P2).

Another major weakness that hinders the DT through PdM and spare parts inventory systems is the lack of technological expertise of PdM integration (P1, P3, P8, P11, P12, P13, P15). Specifically, P11 mentioned that "*the required skills to manage and implement such complex system is lacking*". Organisational stakeholders realise and understand the benefits of implementing such digitalised technologies. Consequently, they argue that it is necessary for companies to take necessary actions to change the mindset of employees and senior management regarding the adoption of PdM, while investments should be made towards employees' development in acquiring the required digital skill sets. Such solutions will help with the adoption and use of these digitalised solutions, thus managing implementation and any related uncertainty. Because of the ambiguities surrounding these solutions, some experts (i.e. P4, P6, P11, P14) reported that employees are scared of losing their jobs, which often creates resistance and delays in the introduction of PdM technologies. In particular experts P4 argued that "*manufacturers fear the idea of no downtime. This would mean that the roles of a maintenance team would be unnecessary and thus many jobs and skills will become redundant, will disappear*."

A major aspect of spare parts inventory management in organisations is their ability to identify the right types and amounts of parts needed to store. With PdM, organisations can be sure that they get the parts they need at the right time. Of course, that needs to come with convincing stakeholders of the business value of such a complex system. As P5 stated *"An autonomous system that orders spare parts must be accurate and it must be monitored properly. It is important to reassure people that we are not taking them out of the process. People like to be in control, and they feel that they will lose power when they are not in control"*. This highlights that such complex implementations are not only digital endeavours, but also encompass a sociotechnical character that requires appropriate organisational nurture and support if these systems are to be adopted and widely used across SC.

Organisational discomfort and innovativeness

The use of a PdM system can enable companies to have an early indication of a potential fault, which will empower them to plan accordingly and consequently to achieve efficient and effective management of their spare parts. As P13 discussed, PdM will help them diagnose problems in advance, but at the same time, they cannot ignore the challenges involved with such complex DT.

Experts from the manufacturing sector (i.e. P5, P8, P9, P10) are concerned with the idea of not having downtime, and being in a situation where there are no machines to be fixed. In other words, this would mean that many maintenance jobs would be unnecessary and, thus, many jobs will disappear and become redundant. Therefore, it is important to change this mindset and create a reassuring environment, where workers understand that such implementations will benefit companies and will create new jobs while replacing many repetitive tasks and processes. A PdM system can save lead time and provide efficiency in all maintenance activities. It reduces costs by reducing the number of people involved in the ordering process, i.e. finance and maintenance teams, as well as minimising errors and mistakes. This can enable organisations to explore digital opportunities while providing them the ability to be competitive and sustainable.

Experts generally agreed that the main challenge they face is the confidence in the system, and the complexity of the suppliers' network (P1, P2, P12, P14, P15): "*How can the system understand that a particular part needs to be ordered from a particular supplier?*" Manufacturers rely on holding close relationships with local suppliers to be able to place orders of spare parts as and when they need them. Suppliers are predominantly those who hold useful data about spare parts inventory, and they are not keen on sharing that information openly. Interviewee P2 highlighted this and mentioned that *"We do not have the right data, and we rely on the data from our suppliers."*

Another issue is the reliability of such an automated spare parts inventory management system (P9, P6, P7). Companies are questioning the extent to which they can rely on the judgment of the system who might recommend for a part to be changed, but potentially that part just needs to be fixed. P1, P5, P8, P9, and P12 asserted that a cultural shift in the mindset of employees is necessary to trust and rely on such an autonomous system. How do you trust and have faith in a machine that will do the same, if not a better job than a human? As P11 clearly stated *"PdM is great if it works"* – the question then remains how can organisations make it work?

Environmental optimism

Manufacturers often pay a premium when a sudden failure occurs, and quick repair is required. In the case, of these emergency orders, companies tend to have certain agreements with spare parts suppliers to get what they need quickly, but they usually achieve this at a great financial cost. On the other hand, *"We keep on our inventory hundreds of thousands worth of spare parts. We keep them in case we need them. This equates to great inventory and workforce costs" (*P14). Either way, the financial penalty is usually significant and must be absorbed in the organisation's operations, which becomes a challenge itself. However, finding a solution to this issue and maximising efficiency on how organisational capital is used is an opportunity that can be materialised with the integration of PdM and spare parts inventory management.

Interestingly, some experts (P8, P11, P12, P15) highlighted that one of the biggest challenges for manufacturers is the lack of skilled people, because the workers with the right skills are getting old and they are no longer in the market. Experts felt that there was a significant shortage of skilled workers when it comes to managing maintenance activities *"the overall skillsets are shifting from a very specialised one to multidisciplinary skills where people should have mixed skills of everything"* (P4). These conditions create further environmental challenges when companies consider investing in the DT of their spare parts inventory management.

4.3. Embracing digital integration of spare parts inventory management and PdM

Digital innovations can change working practices while they can impose their own logic in strategy, culture and processes and since their influence can be seen in different levels, settings and organisational functions it is perceived as a transdisciplinary topic. Even though companies recognise that they have very favourable conditions (i.e., optimism, innovativeness) that enable them to successfully integrate their spare parts inventory management with PdM, they still report a number of inhibitors that pose a risk to the successful implementation of such a digital solution. Researchers (Golightly *et al.*, 2018; Chatterjee *et al.*, 2021) suggest that integrating the TOE framework as well as the Technology readiness approach (as discussed in section 2.3 above) allows us to gain a comprehensive view of the enablers and inhibitors of complex technologies such as PdM. Therefore, the following sections discuss the main aspects that experts consider important factors in supporting (enablers) the implementation of PdM as well as those factors that make such an adoption challenging (inhibitors).

Enablers

A strong enabler for PdM is the vast availability of cloud-based PdM systems in the market that can help the adoption of DT. Most of the interviewed experts did mention that they have computerised maintenance systems in place, which means that their current SC is based on collaboration and exchange of information; thus, this would allow digitalised integration to be more feasible. For example, P4 reiterated that "*most maintenance management software are becoming computerised, and these systems are integrated across the* SC." P3 explained that manufacturers use computerised maintenance software on tablets, enabling them to monitor their business processes more effectively because they receive timely notifications whenever there is a problem on the shopfloor. This phenomenon is supported by the current global trend of digitalisation in the manufacturing sector, as organisations already have the data that they need to implement spare parts inventory management systems and PdM. As P1 argued, "*the shift towards PdM enables us to compete globally and to align our business strategies, which is about highly digitising processes across the* SC" and this consequently makes companies more efficient and effective. Additionally, the availability of data sharing related policies and regulations, such as GDPR, can aid the adoption process, while it helps to reduce the trust issue across the SC becomes less concerning. This is reinforced in the comments of some of the experts (e.g., P9) explaining that "*trust regarding sharing data with third party should not be an issue since GDPR regulations are tightly in place*".

Inhibitors

Despite the favourable aspects that can support and encourage the implementation of spare parts inventory management systems with PdM there are still several factors that tantalise organisations and inhibit the realisation of such beneficial DT across the SC.

There is a great need for better spare parts management, with almost all the experts reporting that there is a shortage of spare parts when they need them. For example, P7 reports that "*there has always been an issue regarding the availability of spare parts, especially when the demand is high*". This means that accurately managing parts demand is a challenge in the current inventory management for spare parts and this causes an issue in tracing parts and thus hinders the ability of an integrated system to be put in place. As P4 confirms "*there is a big problem when the* SC *is disrupted due to the availability of spare parts*". This issue is also directly linked to the lack of availability of sufficient historical and real-time data with P10 saying that "*the system needs to be relying on a data-based approach, so the availability of data is important*". However, most manufacturers have not integrated advanced software across their SC to capture relevant data. P7 explains that "*the availability of the relevant data is very important, we need data analytics that allows the use of the machine learning techniques, which currently, we do not have*".

For companies to be able to capitalise on the benefits of DT, there is a need for interconnectivity and integration between manufacturers and parts suppliers, and currently there is a lot of resistance. P6 discussed that "*top management resistance is a big issue, senior executives show a preference towards the traditional techniques, since the traditional way does not require the high investment costs that are required for an integrated spare parts system*". Additionally, the complicated supply network environment does not help the situation. There are numerous suppliers for various parts that makes it difficult for automated systems to recognise if the required part would need to be new or refurbished, and from which supplier needs to come from. P2 explains that "*a challenge is the complexity of the suppliers' network and how to make the system understand that this part needs to be ordered from a particular supplier*". This raises questions regarding the confidence of such digital systems, and their ability to respond accurately without human intervention.

All the experts described that PdM is inflexible and very costly to fit within an old infrastructure, while P11 states "*there is not enough information about effective implementation of PdM integration with spare parts inventory management*". The implementation of such complex system requires time, which many experts highlighting that they did not have since none of them can afford to shut the factory down in order to set up PdM systems. Few experts were hesitating to initiate such complex implementation, which may not have reliable and accurate data. In line with this, P8 said that "*the level of trust and reliability of such a digital system to order parts it does not seem logically possible*". This further emphasises the concerns of data security and privacy, P9 expressed that "*there is a security concern, especially as data will need to be shared with third parties*".

The technological innovation of integrating PdM and spare parts inventory equips companies with an ability to utilise knowledge to overcome obstacles and achieve improvements at the technical, operational and organisational levels. Without this technological innovation, these companies can fall behind in a highly competitive market, and eventually grow obsolete. It is this risk of losing the competitive edge that forces companies to invest heavily in developing new solutions to retain their position in their industry.

Discussion

The findings show that although there is a strong intention from companies to take the journey towards integrating their spare parts inventory management with PdM, however, they still do not have consistent strategies to face up to the challenges that such an endeavour incorporates. A major shift in digitalisation for these organisations will be the ability to reduce and even eliminate downtimes in machines and therefore improve performance across their SC (Karippur *et al.*, 2024). Our research suggests that there is a strong demand for the proposed integrated solution and indicate a direction towards removing barriers to reap the benefits of PdM across the SC.

While maintenance planning and optimisation have been the subject of extensive research for decades (Errandonea *et al.*, 2020), our findings reveal that organisations are still struggling with the implementation of such complex systems. Such digital systems influence not only the way organisations operate but also the way that employees interact with these new technological advancements and thus, these DT have to be in tune with the companies' vision in order to minimise extensive disruption. The technological journey of achieving integration of a spare parts inventory management system and PdM becomes intertwined with the organisational and human aspects of change management from a sociotechnical perspective. This is consistent with the insights from Marcon *et al.* (2022) who emphasised the sociotechnical configuration of recent DT.

A clear shift in managers' and employees' mindset and organisational culture is necessary in order for companies to realise the value of PdM. However, there is reluctance and scepticism from suppliers as well as top management executives (Golightly *et al.*, 2018) towards the adoption of DT and the challenges it incorporates. The elicited findings from interviews reveal that manufactures are still behind in this journey. What is needed is a clear spare parts inventory management strategy to tackle the current challenges and enable companies to implement technologies that can help them. This becomes a major contribution of this research since most of the current research (Karuppiah *et al.*, 2021) is predominantly focusing on technological aspects that affect DT and have not yet spend sufficient effort to explore the organisational, environmental and social aspects.

From a PdM perspective, collecting data from a piece of equipment, giving contextual information and semantically improving the available data, through the use of information from various perspectives can be a great asset for organisations but it comes with many challenges. The use of predictive technology presents various challenges because many companies are concerned about the accuracy of such a system, while they also question the related security and privacy issues that might arise from such a close data-sharing technology (Cui *et al.*, 2021). The real-time connection of assets and availability of digital devices can improve both spare parts control and inventory management, as well as improving the constant awareness of the assets' real state of health (Brodeur *et al.*, 2023). These technologies can also ensure a more reliable performance by the operators. Furthermore, planning and scheduling can be improved by such a digitalised environment that enables the constant acquisition of feedback to guarantee the optimisation of spare parts inventory management objectives in terms of availability of parts and the efficient use of resources.

Despite all that, investment cost is a key challenge for companies, and this often stops them from initiating PdM solutions (Tortorella *et al.*, 2022). Thus, a financial business model is required to foster savings that can be achieved from maximising the lifetime of the equipment. This will further help organisations understand how PdM can enable them to plan for a potential fault and/or prevent a fault/breakdown, thus saving operational costs (Silvestri *et al.* 2020).

Our study highlights the main enablers and inhibitors that need to be considered before and during the integration of spare parts inventory management and PdM. A clear strategy is deemed to be essential for implementing PdM effectively and optimising spare parts inventory management. This entails shifting the mindset and organisational culture among managers and employees. The findings also underlined the significance of adopting a sociotechnical perspective, recognising that successful DT involves not only technological aspects but also organisational and environmental factors. Another major issue that was brought up by the experts in our study was lack or shortage of relevant data that are required for effective implementation of PdM. This intensifies since there are concerns over sharing data with third parties; companies are concerned that if they provide their data for the purpose of such a system then these might be leaked to their competitors with serious consequences for their operations. Technological innovation, particularly integrating PdM and spare parts inventory management can empower organisations to overcome obstacles and achieve improvements at various levels (i.e., technical, operational, and organisational). Embracing these innovations is crucial for companies to retain their competitive edge and thrive in a highly digitally competitive market.

Conclusion

The present study addressed the need in gaining a holistic understanding of the current capacity and readiness of manufacturing companies in their efforts to digitalise their spare parts inventory systems. The purpose was to understand the integration of spare parts inventory management and PdM while identifying key enablers and inhibitors for achieving successful DT from the implementation of such complex systems across the SC. From a PdM perspective, harnessing data from equipment, contextual information, and semantic improvements can greatly benefit organisations. Several challenges were uncovered including the complexities associated with data integration and implementation. Despite the potential advantages of smart manufacturing innovations and digitalisation, many manufacturers are still in the early stages of adopting PdM due to the difficulty of convincing top management and stakeholders of its value. These organisational barriers still need to be dealt with before PdM is seen favourably by the different organisational actors.

Theoretical Contributions

The article contributes in several ways to the discussion surrounding the integration of spare parts inventory management and PdM. This is the first article to present a holistic study on the readiness of organisations in adopting PdM and the first study to explore the enablers and inhibitors of integrating spare parts inventory with PdM with an approach of interviewing PdM experts. The findings of our study can guide researchers to further map the research needs of the adoption of PdM in various industries. Scholars and academics can use our results to further understand, explore and identify the important factors that act as barriers and enablers in the integration of PdM with spare parts inventory across the SC. Our research contributes to the area of PdM by providing rich insights in the previous limited understanding on the delayed implementation of these complex systems. The key enablers and inhibitors are reported, and their connection is discussed and further interpreted.

Practical / Managerial Implications

Understanding the enablers and inhibitors of digitalisation in spare parts inventory management and PdM presents a valuable opportunity for organisations aiming to implement these intricate systems and digitally transform. The insights gained from expert analysis can serve as a practical guide for companies, both in the manufacturing sector and beyond, as they plan their PdM system implementation. By leveraging this knowledge, organisations can effectively address potential inhibitors, turning them into strengths and advantages through strategic planning. Moreover, the lessons learned from successful integration can be shared across the SC, fostering favourable conditions to overcome the challenges posed by this complex environment and its associated barriers. Our research findings reveal a noteworthy intention among companies to embark on the journey of integrating spare parts inventory management and PdM. However, a significant gap still exists in understanding how to confront the challenges inherent in this endeavour. Nonetheless, the demand for the proposed integrated solution remains strong, signalling a clear direction toward removing barriers and unlocking the benefits of PdM across the SC. Our findings highlight that the implementation of PdM systems, create a compelling opportunity for companies to seize the competitive advantages offered by such DT.

By understanding the enablers and inhibitors of achieving digitalisation between spare parts inventory management and PdM, organisations can use these as a useful guide in their efforts to implement such complex systems. The lessons learnt from the experts can be used from companies in the manufacturing or other sectors to plan the PdM system implementation while it will enable them to either avoid the inhibitors or use them to their strength and advantage by planning appropriately. The knowledge of how to go towards achieving the desired integration can aid partners across the SC to create favourable conditions so that they can overcome the challenges of the complex environment and the barriers it encompasses.

Limitations of the study and recommendations for future research

Despite the interesting findings that we discovered through our in-depth analysis, this study has some limitations. Our study was limited to a group of organisations in the manufacturing sector resulting in a modest sample size. This can be extended to cover more organisations with the possibility of more in-depth comparative analysis among organisations from different sectors, and various sizes. Therefore, future studies in the format of a case study can leverage organisational insights and further inform business models and investment considerations. An interesting finding was that managers and employees need to shift their current mindset and the organisational culture needs to change before PdM is embraced in organisations. Future research can investigate this in greater detail and explore the best way to introduce such a complex system in an organisation's values and attitudes. Simulation or mathematical modelling studies can also contribute to quantifying system adoption and migration costs and benefits that can also be replicated in real-world scenarios of DT journeys. Thus, the environmental and economic benefits of such an integration can be further researched. Additionally, the applications of such complex integration can be of great interest in other industries including wind turbines, commercial aircrafts, and nuclear power plants. Finally, the integration of PdM and spare part inventory management with other I4.0 technologies such as 3D printing can be also explored.

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Appendices

Figure 1

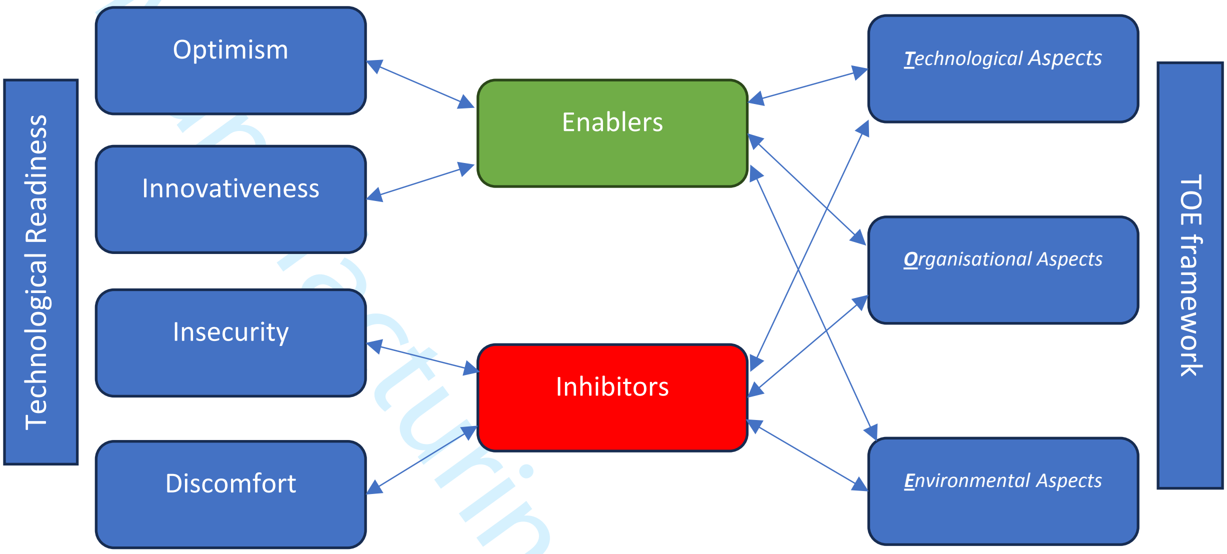
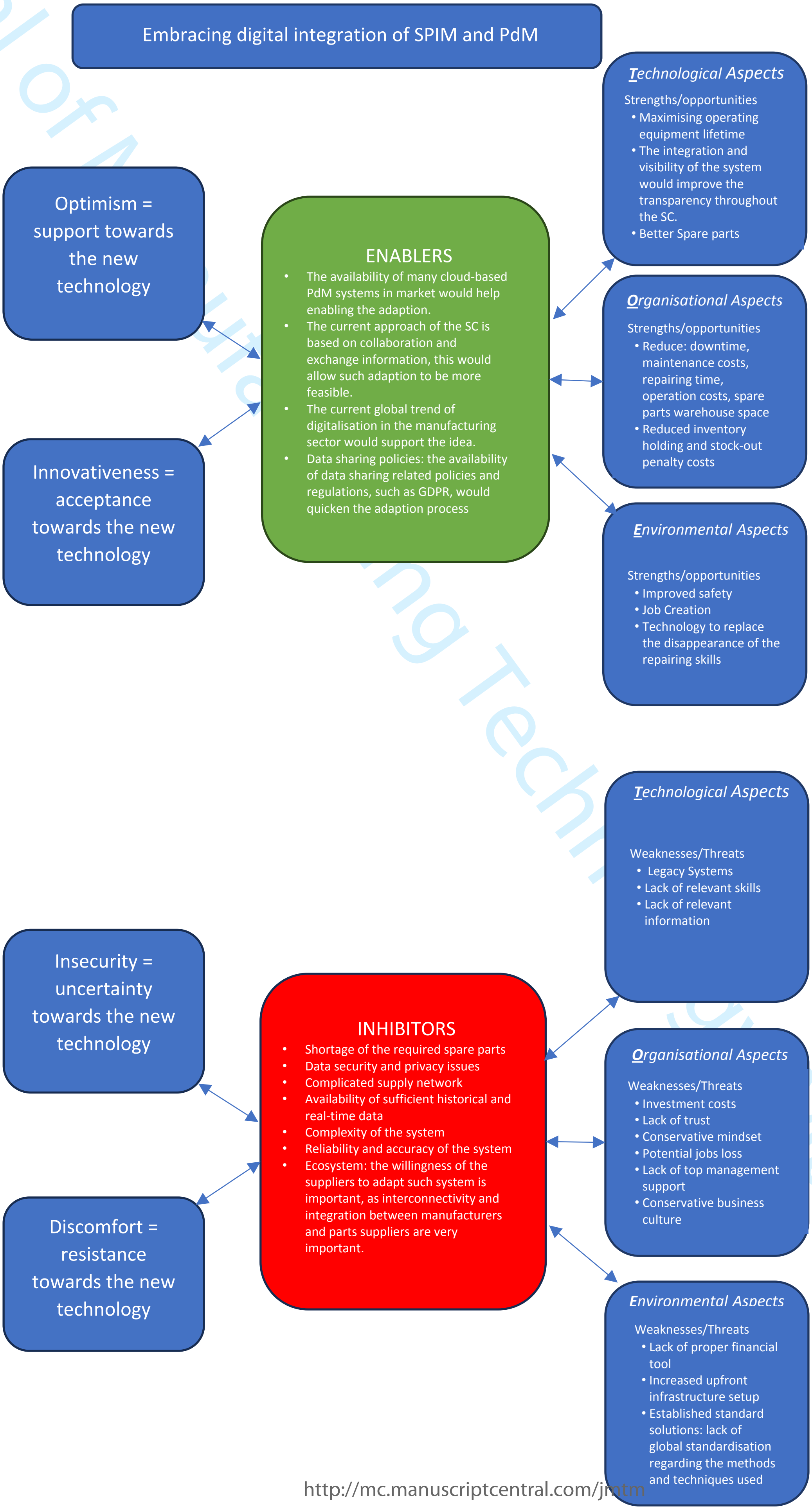


Figure 2


Embracing digital integration of SPIM and PdM
Optimism = support towards the new technology
Innovativeness = acceptance towards the new technology
ENABLERS
The availability of many cloud-based PdM systems in market would help enabling the adaption.
The current approach of the SC is based on collaboration and exchange information, this would allow such adaption to be more feasible.
The current global trend of digitalisation in the manufacturing sector would support the idea.
Data sharing policies: the availability of data sharing related policies and regulations, such as GDPR, would quicken the adaption process
Technological Aspects
Strengths/opportunities
Maximising operating equipment lifetime
The integration and visibility of the system would improve the transparency throughout the SC.
Better Spare parts
Organisational Aspects
Strengths/opportunities
Reduce: downtime, maintenance costs, repairing time, operation costs, spare parts warehouse space
Reduced inventory holding and stock-out penalty costs
Environmental Aspects
Strengths/opportunities
Improved safety
Job Creation
Technology to replace the disappearance of the repairing skills
Insecurity = uncertainty towards the new technology
Discomfort = resistance towards the new technology
INHIBITORS
Shortage of the required spare parts
Data security and privacy issues
Complicated supply network
Availability of sufficient historical and real-time data
Complexity of the system
Reliability and accuracy of the system
Ecosystem: the willingness of the suppliers to adapt such system is important, as interconnectivity and integration between manufacturers and parts suppliers are very important.
Technological Aspects
Weaknesses/Threats
Legacy Systems
Lack of relevant skills
Lack of relevant information
Organisational Aspects
Weaknesses/Threats
Investment costs
Lack of trust
Conservative mindset
Potential jobs loss
Lack of top management support
Conservative business culture
Environmental Aspects
Weaknesses/Threats
Lack of proper financial tool
Increased upfront infrastructure setup
Established standard solutions: lack of global standardisation regarding the methods and techniques used