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Exploring the impacts and contributions of maintenance function for sustainable manufacturing

Maria Holgado^{a*}, Marco Macchi^b and Stephen Evans^c

^a*Department of Management, University of Sussex, Brighton, United Kingdom;*

^b*Department of Management, Economics and Industrial Engineering, Politecnico di Milano, Milan, Italy*

^c*Institute for Manufacturing, Department of Engineering, University of Cambridge, Cambridge, United Kingdom*

*corresponding author

Abstract: This investigation studies advanced practitioners of maintenance management and seeks to uncover the related impacts and contributions of best practice maintenance toward sustainable manufacturing operations. This exploratory research conducted a novel empirical analysis focused on maintenance functions in nine manufacturing companies from diverse sectors. The analysis uncovered insights related to the economic, environmental, and social benefits of a deeper involvement of maintenance function in plant operations and decision-making. We observed links of maintenance function with product competitiveness and with energy management activities that were unexpected. We confirmed benefits from keeping machinery in good working conditions and restoring promptly good working conditions when an issue happens. The depth of maintenance contribution on each area identified in this study will depend on the operational and business context of the manufacturing company; thus, companies need to reflect on these based on their specific processes, business needs and goals. Ultimately, this work can inspire managers

in manufacturing companies to organise maintenance function strategically toward fostering long-term competitive, responsible and sustainable performance.

Keywords: maintenance, maintenance management, maintenance strategy, responsible manufacturing, sustainable manufacturing, triple-bottom-line (TBL)

1. Introduction

Production systems have a huge impact on environment and society due to their intensive use of natural resources and labour, and to the effects of their operations. Moving away from the assumption of unlimited natural resources, production management and research should support a more sustainable society creating value from better physical, economic, psychological and environmental outcomes (Ishii, 2013). Manufacturing companies are challenged to address these issues by integrating sustainable and responsible practices in their sourcing, production and distribution processes. Building on previous definitions (Rachuri et al. 2011; Despeisse et al. 2012), sustainable and responsible manufacturing aims at transforming input resources, through environmentally and socially sound processes and techniques that minimise resource consumption, eliminate health hazards and produce zero waste, into products and / or solutions that are safe for consumers and communities, while preserving natural resources and eliminating waste along their entire life cycle. This implies a higher responsibility of manufacturing companies over the environmental and societal impacts along the whole life cycle of their products as well as of their production processes and assets. Indeed, the IET (2019) suggests companies to progress towards sustainable manufacturing by focusing on non-labour resource productivity (energy, water and raw materials), and by making sure that all processes are lean, efficient, and effective. Maintenance, as a key function within manufacturing for better asset and resources utilisation, conservation and useful life extension, would be expected to be a central

area of inquiry in sustainability studies. However, this is not the case, and maintenance and sustainability research have occasionally encountered.

Many aspects of maintenance contribution to sustainability in manufacturing remain unexplored, such as the identification of all maintenance-related sustainability impacts and of maintenance actions mitigating those impacts (Franciosi et al. 2018), and the wider understanding of maintenance contribution to eco-efficiency (Ball and Lunt 2018a). Since Garetti and Taisch (2012) reflected on maintenance as a lever to advance towards sustainable performance in manufacturing, few studies have taken this forward. An earlier work suggested that sustainability improvements emerge from close cooperation between maintenance and other manufacturing operations (Liyanage 2007). Most recent contributions focused on enriching maintenance decision making by integrating environmental considerations in the design of maintenance strategies and plans (e.g. Ajukumar and Gandhi 2013; Ighravwe and Oke 2017), and on exploring synergies of quality and lean approaches with maintenance practices (e.g. Ball and Lunt 2018a; Sahoo 2018). It is evident that, at the current state of the art, studies over maintenance as a lever to advance towards sustainable performance in manufacturing are still scattered, while more holistic research appears a need in this area, in order to provide a comprehensive outline of the role and the capabilities of maintenance function for sustainable manufacturing.

This research presents a novel empirical study on the impacts and contributions of maintenance function to more sustainable operations in manufacturing companies. This exploratory research takes a multi-sector perspective covering a range of manufacturing operations rather than limiting the study to a specific sector. This helps to build a comprehensive view of maintenance contributions while avoiding biases from sectorial features. Nine case companies were investigated to build an overview of

sustainability impacts of maintenance function and how maintenance actions may improve or hinder sustainability performance.

The article is organised as follows. Section 2 presents a background review on the strategic importance of maintenance and its envisaged connection to sustainability. Section 3 describes the research methodology followed in the empirical study. Section 4 presents and discusses the results of this study, followed by conclusions, implications and recommendations in Section 5.

2. Background

2.1 Strategic importance of maintenance in manufacturing

A function within manufacturing companies that has been frequently the preferred target for outsourcing strategies and pointed out as a cost centre (Campbell 1995; Kumar 2008), maintenance has slowly progressed towards higher recognition as a source of value for production systems (Marais and Saleh 2009; Naughton and Tiernan 2012) and a contributor to company's productivity and profitability (Alsyouf 2007; Maletič et al. 2014). These works suggested a contribution of maintenance to company's financial value in specific ways. For example, Marais and Saleh (2009) propose a quantification technique to determine the value of maintenance based on the net revenue generated by the production system with and without maintenance activities. Naughton and Tiernan (2012) suggest using specific economic indicators, e.g. the return on net investment in maintenance, when designing the maintenance strategy, as a means to quantify the maintenance contribution to financial performance. Alsyouf (2007) illustrates empirically how different maintenance policies influence productivity, linking this also to the company's profitability through its direct impact on quality, efficiency and effectiveness of operations. Quality, productivity and profitability are

identified as key elements for the selection of adequate maintenance policies in the empirical study done by Maletič et al. (2014).

The competitive business environment, increasingly focusing on customer value via improved production efficiency, and putting more pressure on retaining production assets value over time, has served to promote maintenance recognition as a strategic function for manufacturing companies. This implies utilising maintenance management consistently with the business strategy (Simões, Gomes, and Yasin 2016) and with the manufacturing strategy. The alignment of maintenance strategy with manufacturing and business strategies has been subject of study within maintenance management frameworks (e.g. Kelly 2006; Pinjala, Pintelon, and Vereecke, 2006; Crespo Marquez et al. 2009). Defining an adequate maintenance strategy is seen as a means to transform company' objectives into maintenance objectives (Velmurugan and Dhingra 2015). Maintenance objectives are typically defined at initial phases in frameworks or methodologies, by exploiting techniques for the alignment with the operational and overall business strategy. For example, Balanced Scorecard (BSC) is suggested to define maintenance objectives and strategy, to inform employees of the pursued strategy, as well to track the effectiveness of action plans in meeting the strategic objectives (Crespo Marquez et al. 2009). This strategic role of maintenance can also support performance improvements that deliver business value from a long-term perspective, through the conceptualisation and implementation of a maintenance business model (Holgado, Macchi, and Fumagalli 2015).

Overall, the links of maintenance with profitability and strategic competitiveness of manufacturing companies have been extensively covered in maintenance research and literature during the last two decades. They are widely accepted and mainstream in maintenance literature, constituting a strong connection with the economic perspective

of business sustainability. Beyond this evidence, maintenance contributions to environmental and social aspects of business performance remain an under explored research area. Insights regarding this current state-of-the-art are provided next.

2.2 Sustainability and maintenance

This section first reviews works within maintenance studies that address certain aspects of sustainability. Then, it covers how maintenance is presented in sustainability studies.

Remarkable and well established in literature is the contribution of maintenance to safety of production systems. For example, safety, i.e. safety of personnel, equipment, buildings and environment in the event of a failure, is considered alongside economic and production indicators for the definition of a maintenance strategy (Bevilacqua and Braglia, 2000). An enlarged scope for maintenance arose from adopting a life cycle perspective towards production assets, and this led to the emergence of initial considerations on environmental sustainability. Maintenance can help ensuring that production assets provide the required functions along their lifetime while minimizing material and energy consumption (Takata et al. 2004). This asset lifecycle perspective has been studied mainly from a conceptual viewpoint. Examples of maintenance-oriented works in this area are a proposal of whole-life objectives for maintenance function (Levrat, Iung, and Crespo Marquez 2008) and a methodology for maintenance decision making to extend the asset useful life (Yan et al. 2012). Adopting a lifecycle perspective is also fundamental for cascading business sustainability policies to production assets as discussed by Liyanage, Badurdeen and Ratnayake (2009).

Most maintenance studies are still mainly focused on conventional performance measures (Franciosi et al. 2018), with limited contributions looking at enlarging maintenance performance scope to environmental and social considerations. For

example, Marais and Saleh (2009) acknowledge that additional value dimensions related to environmental or health impacts, or safety and regulatory requirements, although not included in their method, could be explored to quantify the value of maintenance activities. Energy consumption and efficiency aspects have been more often addressed in maintenance literature (Demirbas 2008; Tousley 2010). In area, Xu and Cao (2014) study energy efficiency improvements through effective maintenance operations scheduling, and Hoang, Do, and Iung (2017) propose an energy efficiency indicator and the concept of Remaining Energy Efficiency Lifetime (REEL) to support maintenance decision-making. Moreover, Ndhaief et al. (2020) investigate the modelling of joint production and maintenance plans with carbon emission constraints. A wider scope of environment or social aspects have been included in specific applications of multi-criteria decision-making methods. For example, Ajukumar and Gandhi (2013) proposed an evaluation model for equipment design that includes maintenance requirements related to environmental considerations. Savino, Macchi, and Mazza (2015) propose a ranking model to assign maintenance policies by considering social issues related to age and gender and workers' know-how. Ighravwe and Oke (2017) used environmental factors in their ranking method that were obtained from waste management, health and safety, and environmental management literatures, as they report lack of defined factors on the impact of maintenance on the natural environment in maintenance literature. In this line, Pires et al. (2016) propose a set of triple-bottom-line (TBL) factors for maintenance, which are inspired on the GRI guidelines for business sustainability reporting.

Ultimately, it is worth observing that few maintenance studies have explored the adoption of maintenance methodologies and techniques to improve sustainability aspects. They mainly focused on investigating synergies between quality and

maintenance, e.g. between Total Quality Management (TQM) and Total Productive Maintenance (TPM) implementations (Sahoo 2018; Kaur, Singh, and Ahuja 2013). Ball and Lunt (2018a) developed innovation-led lean activities through maintenance to enhance eco-efficiency, advancing the research on synergies between lean, maintenance and sustainability. Besides this, there is limited contribution of maintenance literature to central concepts in the sustainability literature, i.e. Product-Service-Systems (PSS) (e.g. Tukker 2004; Vezzoli et al. 2015) and Circular Economy (CE) (e.g. Bocken et al. 2016) which are deemed as means to achieve more sustainable industrial systems. Conceptual links have been suggested, inspired mainly by maintenance lifecycle support, as well as by maintenance technologies for PSS (Liyanage, Badurdeen and Ratnayake 2009; Jung and Levrat 2014), and by maintenance regenerative capacity for CE (Diez et al. 2016).

Looking at how maintenance is presented in sustainability literature, it is worth observing that few sustainability-related studies suggest an impact of maintenance actions in the overall sustainability performance of industrial systems. PSS and CE studies often present a narrow view of maintenance function, solely understood as repair and corrective interventions to maintain products or assets functionalities during their usage time. For example, Bocken et al. (2016) consider that design strategies for product maintainability and easiness of repair, among others, contribute to slowing resource loops, and Tukker (2015) recognises the potential for some environmental gains through better maintenance in the product use stage, within product-oriented PSS. The PSS literature mainly consider maintenance at the lower value-adding product-oriented PSS. Amongst the few exceptions, Gaiardelli et al. (2014) also include maintenance performance management within result-oriented PSS offerings, which is the PSS type with higher potential for value-adding and sustainability gains (Tukker 2004). In general, sustainability studies are neglecting the role of maintenance along the

whole product and asset lifecycle. The limited understanding of the actual scope of maintenance function hinders more substantial contributions to these sustainability frameworks.

Overall, while maintenance studies show promising insights on specific sustainability aspects, this section brings evidence of the lack of a holistic view of maintenance potential for sustainability in sustainability studies and of a solid connection between these two literatures.

3. Method

The research question for this study emerged through a *problematization* methodology applied to the existing literature (Alvesson and Sandberg, 2011). The survey of literature uncovered maintenance as a neglected area in the efforts to operationalise sustainability in production research. Thus, this required further investigation as it could be a missing piece preventing the advancement of this research field and preventing companies from realising the full potential of their maintenance approaches and operations for achieving sustainability. The research question was then defined as follows: What are the impacts and contributions of maintenance actions for sustainability in manufacturing? Exploring such implications is a fundamental step to go forward in the operationalisation of maintenance and sustainability linkages.

This work presents an exploratory study that aims at identifying the wide range of potential impacts and contributions of maintenance function using case study methodology. The approach taken is a multi-case method focusing on maintenance functions in manufacturing plants belonging to companies from different sectors. The multi-case approach gives breadth to the study and allows a comprehensive understanding of the phenomenon rather than narrowing to the specifics of a particular sector. It brings compelling and robust evidence on a phenomenon in exploratory

studies (Yin 2003). Details of the research design are provided in next subsections and an overview is shown in Figure 1.

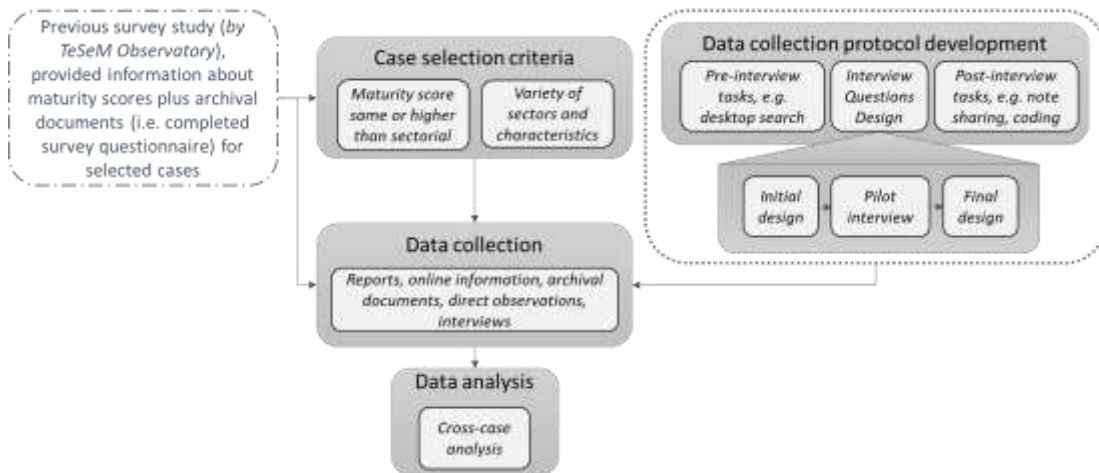


Figure 1. Research Design

3.1 Case selection

The case studies were selected with an instrumental interest, i.e. based on their potential to provide insights into the phenomenon under study (Stake 1995). To maximise the learning from these instrumental case studies, the case selection criteria targeted varied sectors and product complexities while ensuring that the maintenance functions were of high standard, i.e. including well-organised and high-performing maintenance functions. To identify maintenance functions of high standards, the results of a previous survey study, conducted by the Technologies and Services for Maintenance (TeSeM) Observatory, were used to help selecting case companies. Particularly, the maturity assessment study conducted through a survey of technological, organisational and managerial capabilities of maintenance functions in manufacturing companies (Macchi and Fumagalli, 2013), offered a good proxy to select stable and well-organised maintenance functions. Here we used their General Maturity Index (GMI), in the remainder Maturity Level (ML) for simplicity, which is composed

of three component indexes: Management Maturity Index (MMI), Organizational Maturity Index (OMI), Technological Maturity Index (TMI), as proposed in their method. They defined the ML scores in five levels (5 being the highest maturity) with two additional degrees (low and high) to create sub-levels; therefore, the highest possible score was ML5-high while the lowest possible score was ML1-low. The TeSeM survey received 118 responses from Italian-based manufacturing plants distributed across the following sectors: food/beverage (33%), chemical/pharma (18%), machinery (17%), electronics (7%), automotive (6%), rubber/plastic (6%), metal (5%), textile (4%), others (2%). The maximum score obtained from the survey results was ML5-low, which belonged to two companies in the food sector and one company in the energy sector. None of them were included in this study due to unavailability and geographical distance. Among the 118 Italy-based manufacturing plants that completed the survey questionnaire, those that scored equal or higher than their sectorial average score were initial targets for the study. Then, the criteria of variety of sectors, markets, and product complexities was used to narrow down the list. Additionally, all production plants selected were also convenient to visit by the researchers involved in data collection.

3.2 Data collection and analysis

The final sample included nine cases, whose details are shown in Table 1. The diverse background of the cases enhances the external validity of findings. Reliability issues were tackled by developing a case protocol and obtaining information from multiple sources of data: interviews, documents, archival data, and direct observations (Yin 2003). The case protocol included pre-interview tasks to gain initial understanding of the status of maintenance capabilities and processes in the plant, through desktop search

of company information, documentation available online, and the TeSeM survey questionnaire. The interviews followed a semi-structured approach and were conducted in the company premises, either their manufacturing plants or headquarters. The interview questions were tested in an independent pilot case. This testing revealed an issue when the term ‘sustainability’ was directly used in the questions. These questions were re-worded by removing the ‘sustainability’ term from them; instead, dimensions and elements of industrial sustainability, from Arena et al. (2009), were used in framing the questions. After its revision, based on the feedback obtained, it was considered suitable to confidently capture the desired insights from the interviewees. The final version of the interview questions is provided as Appendix 1. The selected interviewees were maintenance managers (MMs) of production assets and facilities or other managers with responsibility over maintenance function according to the organisational structure, i.e. technical managers (TM) or operations managers (OM); their job positions are presented in Table 1. The interviewees of each case were considered key informants for gathering deeper insights due to their first-hand experience and overseeing responsibility over maintenance function. Their identification was informed by the research question, the unit of analysis and the scope of research, as recommended by Krause et al. (2018).

After each interview, the interview notes and recordings were revised and the recordings (approx. 10 hours) transcribed. Additional follow-ups were done based on responses or documents provided during the interview. For the interview that was not recorded, due to company regulations, a report was created immediately after the interview by confronting notes from the researchers. Interview data was analysed using a set of pre-defined categories for exploratory coding (Saldaña 2009). Two categories concerned the setting of maintenance function, i.e. business context and maintenance

organizational context, another category was assigned to the identification of maintenance stakeholders, and the other four categories referred to economic, environmental, social, and technology / innovation aspects, respectively. The cross-case analysis grouped all coded text in each category subsequently into further subcategories. Some coded texts belonged to two or more categories; this was tracked along the analysis process within each category. For example, most coded texts within the stakeholder category were also linked to maintenance context or social categories, similarly most coded texts within the technology / innovation category were linked to economic, environmental or social categories. In these situations, following common practice in sustainable manufacturing studies (Eslami et al., 2018) the TBL categories were prioritised. Triangulation was enabled by contrasting the interview information with available secondary data collected for each case, e.g. TeSeM survey questionnaire, Orbis database, available company documents.

[Insert Table 1]

4. Results

This section first presents the context in which maintenance function operates and the strategic decisions related to maintenance organisational design in these companies.

Then it introduces the results regarding the economic, environmental and social dimensions; this aligns with the way of presenting results in most sustainability studies in manufacturing (Eslami et al. 2018).

4.1 Organisational structure and strategic scope of maintenance function

The maintenance function in these companies reports either to the on-site technical

office (T1, E1, C3) or directly to the plant management (C2, E2, M1, F1). C1 has an interesting organisational structure in which maintenance function belongs to the technical office and the production function is subordinate to this technical office. Only the organisational structure of A1 puts maintenance directly under production function. Thus, only A1 follows a “traditional” organisational structure for maintenance that has been linked to lower operational efficiency (Tsang 2002).

The equal organisational status of maintenance respect to other business functions reflects a search for higher operational efficiency as well as an increasing recognition of maintenance value. The MM in M1 experienced the change to this new organizational status, and explains that maintenance has gained its own identity after the change; it reports now directly to plant management, has more autonomy to manage its resources, to develop a dedicated team for maintenance engineering, and more visibility and responsibilities in the whole plant activities and facilities.

All interviewees agree that the role of maintenance function is somehow recognised as a contributor to company’s goals and strategic priorities. For example, an internal document from C3 made available to this study regards maintenance as ‘*an element of competitive distinction*’. Each interviewee explained what the company strategic priorities are and how maintenance contributes to them. Changes in the business strategy and positioning in C1 had direct implications for maintenance function. In particular, a stronger focus on analysing safety and environmental impacts within company operations implied the creation of new classifications for maintenance interventions, and their related expenses, to cover these aspects. According to the OM in C1, this led to better understanding of the contribution of maintenance regarding safety conditions and environmental impacts.

“There is actually this transition from maintenance seen as a cost centre, to instead a unit that can give value, a strategic contribution to business that can move the business forward. This is a bit what has changed compared to before, because it is requested to be more competitive and the competitiveness is made through all business units” (MM, C3)

“So by integrating everything we try to give more value to the maintenance that, as I said, taken alone sometimes is maybe a fee, let's say the fee I have to pay to move forward” (OM, C1)

The ubiquity of maintenance function and its links to other functions within the plant management enlarges the scope of maintenance operations and creates a multidisciplinary working environment in most of these companies.

“It would be difficult for me to find an area in which maintenance is excluded” (OM, F1)

“In theory it would be necessary to integrate everything beyond those who are at the highest level, who have an overall vision, but each [function] should feel the problems of the others, see what the problems of others are that you indirectly at the first level or second level can go to influence; then it will be strongly unbalanced in our case [maintenance function] towards energy management and production” (TM, T1)

Having a maintenance vision that integrates with other functions of the plant, brings benefits in terms of identifying solutions rather than tackling problems in isolation. In C1, this integrated view has translated into higher process efficiency, through redesign, renovation or proactive interventions in manufacturing facilities. Maintenance managers are deemed to have a wider vision of the things that happen in the plant and the business needs, according to the interviewees from C1 and C3. In this regard, the responsibilities of maintenance function have been enlarged to other business areas, such as investigation of non-quality complaints from customers (F1), energy efficiency improvements (E1, E2, A1, M1, F1), management of non-functional buildings (C1, M1, C3, F1, A1), management of plant utilities distribution network (M1), interaction and

relationship with auditors (C2, C3) and management of the integrated management system for quality, safety and environment, and their related certification processes (E2, C3).

4.1.1 Summary of findings and remarks

These findings suggest that maintenance is becoming an important function in these manufacturing plants, with managerial responsibilities and value-adding contributions to business performance, rather than being a subordinate of the production function. The maintenance function is changing in different ways: i) enlarging links to other functions within the plant management; ii) adopting a more integrated view, implying even decisions in the lifecycle (redesign, renovation) or, in general, a proactive approach to interventions; iii) enlarging the responsibilities to contribute to solving problems of other business areas. The role of the MM is then changing. Within the cases analysed, we can remark that the MM is: i) gaining more autonomy to manage its resources, more visibility and responsibilities in the whole plant activities and facilities; ii) having a far-reaching vision of the things that happen in the plant and the business needs; iii) recognised as a contributor to company's goals and strategic priorities.

4.2 Economic dimension of maintenance

This section presents the results related to the economic impact of maintenance on business financial health and profitability, including a reflection on difficulties encountered in measuring certain types of benefits and costs related to maintenance.

All case companies have an annual budget for maintenance; only one company reports a lack of negotiation on that budget while others indicate that the budget is agreed annually with the plant management. The maintenance budget is used for forecasting and controlling maintenance costs, for planning maintenance interventions

and continuous improvements actions. The overall costs of maintenance function do not only involve the direct costs of maintenance interventions, but also indirect costs e.g. spare parts inventory or tools acquisition. Having a negotiated budget helped MMs to arrange more proactive maintenance, i.e. preventive / predictive, rather than corrective interventions (C1, C2, M1). C1 has developed a new system to track the expenses of planned maintenance interventions based on their outcome, i.e. related to safety conditions, input resource savings, product quality, etc. Categorising the budget entries respect to outcomes had two main benefits: (1) it makes evident the value of planned interventions; (2) it allows more control on maintenance costs, i.e. where and how expenses were incurred. This resulted also on a shift to more proactive maintenance and helped to secure its budget and organise maintenance resources more effectively. C2 experienced a similar shift from a reactive (i.e. based on corrective maintenance) to a more proactive approach, which included investing resources and capital on preventive maintenance plans, acquisition of new IT technology and machinery upgrades.

The level of autonomy of maintenance function is somehow related to their availability to manage their own budget. For example, the MM in M1 considers that the new status of maintenance function has raised its budget, enabled new investments, and brought direct responsibilities to manage the budget according to business requirements, and to justify its non-achievements. The MM in C3 has similar budget responsibilities.

“An increase in the budget, surely yes... the fact of having more spending power in respect of certain matters that we have been able to carry on. We have also had the opportunity to make an investment plan and to have more resources, to use maintenance to make extraordinary maintenance interventions” (MM, M1)

“A maintenance manager today is asked not only to be a technician, but [the maintenance manager] must also manage the material resources of the company, that is what is provided, must manage the maintenance budget in a logic of company’s profit” (MM, C3)

The hidden costs of maintenance are more difficult to quantify. They can have a higher impact on company's productivity and profit, and are considered leading factors to drive management attention (Cigolini et al. 2008). A summary of the hidden costs revealed by the interviewees is provided in Table 2, with exemplary quotes.

[Insert Table 2]

As part of an initiative to reduce the number of consumer complaints, F1 is looking at the causes of non-quality events in their final products in a systematic manner, using the Root Cause Analysis (RCA). This maintenance engineering technique is here used to investigate non-desirable events outside the traditional maintenance arena.

Additional interesting insights emerged in relation to product competitiveness (T1, F1, C3, E3) and process reliability (C1, C2, C3, T1, E1, M1). The importance of keeping a good reliability of the manufacturing process was often highlighted as a means to pursue key competitive priorities such as quality and delivery punctuality. The quality emphasis was higher for those producing specialty products.

“A plant that produces these products with high added value is a plant that is very meticulous, the availability factor is very high, therefore on those systems a very high reliability is required” (MM, C3)

“If quality is your premium and you have to keep high quality to stay on the market you have to make sure that also the technical part of the plant is able to give you that” (TM, T1)

"A good maintenance is one of the bases, not the only one clearly, for a good product" (TM, T1)

Due to, partly, the above-mentioned hidden economic impacts that are difficult to measure, there are still challenges to show precisely the value of maintenance. The OM in C1 mentions, “*maintenance function is called out when something does not work,*

thus only [its] inefficiency is measured” and the interviewees from M1 and T1 suggest that one of the barriers to see maintenance contribution more clearly is the difficulty to measure quantitatively its benefits.

“I have also tried to do quantity a lot but no quantification is objective as to such a measure like an objective data from a machine such as temperature, flow, pressure... or the revenue of a sale” (MM, M1)

“If you do not do maintenance, at the end of the year you can try to quantify how much it costed you not to do maintenance, you can try to quantify what you have spent on reworks, the costs of machine downtime, etc. If you do maintenance, you can quantify how much you spent but you can hardly quantify what you saved” (TM, T1)

The difficulties in measuring its effect on production process efficiency may have an impact on the resources made available to maintenance function. The MM in E2 shares *"in my opinion more or less in all companies, they [maintenance function] are all undersized because nobody knows why maintenance is needed"*. Once this is understood, companies seem to be willing to invest in maintenance.

“The owners [of the company] have realized that to step up in class it is necessary to invest on maintenance” (MM, M1)

“Where the current level of availability required for the equipment is not reached, the company is now very willing to spend in order to increase the reliability level and thus the availability associated” (MM, C3)

4.2.1 Summary of findings and remarks

There is good evidence to suggest that the financial health and profitability of the case companies has been positively influenced by the maintenance function through cost reduction, productivity improvements, higher reliability (leading to improved quality and delivery punctuality) and specific contributions to product competitiveness (reported in four cases). In particular, these companies see a link between maintenance

and the final product in the market. This link is remarkable as it has not been identified in previous works. It represents an interesting area for deepening further research.

We also observe that when there is a higher status of the maintenance function within the plant organisational structure, this leads to higher autonomy and responsibility in managing a dedicated budget and making investment decisions.

Moreover, our findings confirm difficulties in measuring quantitatively the hidden economic impacts of maintenance. This is aligned with previous works that reflect on the difficulties of measuring actual maintenance costs and performance achievements (Simões, Gomes, and Yasin 2016). Concepts like the ‘Cost of Poor Maintenance’ can advance practice and increase visibility of maintenance economic impacts (Salonen and Deleryd 2011), although not widely adopted. This demonstrates space for further investigation on increasing this visibility through improved performance measurement systems.

4.3 Environmental dimension of maintenance

Environmental aspects observed relate to input resources and outcomes, as well as inefficiencies in the production process itself. In addition, it is worth noting that the observations regarding transforming input resources, i.e. production machinery and facilities, extend to all their lifecycle phases.

The first observations regard the impact on resource consumption, i.e. on input materials, air, gases, water and energy. Whenever the equipment is not properly maintained, it can cause material losses, quality losses or downgraded outcomes, less tolerance of input materials (T1, E1, C3). The latter is explained as “*especially in the mould or cold press if they are not properly maintained, they degrade and degrading they cannot work input materials which are less noble, so having to throw tons of*

materials that, although within the specifications given to supplier, cannot be worked on the machine” (TM, E1). Leakages and unwanted dispersion of air/gases, which increase input consumption, can be reduced by maintenance interventions (C1, C2, T1, E1, E2). For example, preventive maintenance helps keeping filters on good performance conditions, with the additional benefit of releasing air in good conditions to the atmosphere. Interventions related to improvement maintenance¹ in C2 reduced water temperature and, consequently, reduced water consumption. Also, machinery working out of ideal conditions can lead to higher energy consumption (T1).

“It [production line with mechanical problems] could consume more, it has problems mechanically, there are more frictions and therefore it takes more energy to be able to operate it therefore loses time, and for equal time, it consumes more power” (TM, T1)

The analysis uncovered insights related to the benefits of keeping machinery in good working conditions and of restoring promptly good working conditions when an issue happens, i.e. of performing preventive interventions and of being ready for timely / effective corrective maintenance interventions when a machine is not performing well, respectively. The degree in which these benefits are perceived as important seems to be context and production process dependent. For example, the OM in F1 states that the impact on utilities consumption is high while the TM in E1 considers it low, while acknowledging losses related to leakages can be avoided by maintenance interventions.

¹ Improvement maintenance is defined as the combination of all technical, administrative and managerial actions, intended to ameliorate the reliability and/or the maintainability and/or the safety of an item, without changing the original function (UNI EN 2010).

The MM in E2 regards the impact as high for air and energy consumption but insignificant for water consumption, as water is barely used in the process.

Most maintenance activities and interventions occur within the boundaries of the factory or the production facilities. Interestingly, C3 owns also distribution pipelines. The MM sees a link to land and biodiversity aspects; when they perform maintenance interventions in public land or private farms, they take actions to restore the natural habitat afterwards. For the MM in C2, the impact on natural habitat conservation of maintenance regards the confinement of environmental damage, the treatment of emissions (according to regulations), and the performance of filters for oil fumes.

The data analysis showed strong links between maintenance function and energy management in these companies. Four types of relations between maintenance and energy management emerged in the analysis:

- Maintenance has no formal responsibilities on energy management but engages in dialogue and collaboration with energy management (T1, E1, C2, C3);
- Maintenance has formal responsibilities, acting as support for energy management (C1, A1);
- Maintenance has direct responsibilities for energy management, as secondary activity (F1);
- Maintenance has direct responsibilities for energy management, as primary activity (E2, M1). Here, the MM is acting as energy manager for the production plant.

Informal engagement regard positive effects observed in energy savings (T1), improvement ideas coming from maintenance personnel adopted to reduce energy consumption (E1), improvement maintenance interventions leading to energy efficiency

improvements (C2), support for energy management decisions, e.g. informing on expected versus actual equipment reliability based on maintenance data and experience (C3).

In C1, the responsibilities for maintenance as support to energy management are related to the monitoring of energy consumption and energy power factors, and to troubleshoot energy losses and disturbances to prevent energy inefficiencies. In A1, they also measure energy inefficiency related to equipment degradation. A more comprehensive set of responsibilities is given to maintenance in F1, where the MM has responsibilities for energy management, as a secondary activity. Additional tasks include energy analysis of facilities, definition of corrective and improvement plans for the identified critical issues, operator training on energy efficiency, use of failure analysis techniques for energy inefficiencies, and use of energy consumption analysis as a technique for condition-based maintenance. The energy consumption analysis as a technique is a widespread activity in the nine plants that this company owns in Italy (according to archival documentation made available for this study).

M1 and E2 represent the wider scope of involvement, as maintenance has direct responsibilities for energy management. The MM in M1, who has responsibility on plant utilities, is acting as energy manager to some extent (there is no energy manager officially). The maintenance team first performed an energy audit, followed by maintenance interventions to save energy and improve energy efficiency. E2 shows the strongest links between maintenance and energy. Holding all responsibilities described so far, the MM is indeed acting as energy manager for the whole plant (not only production facilities). However, it is done without any supporting staff and without holding an official energy manager position in the company. Here maintenance-energy is a strengthened and innate synergy.

The contribution of maintenance regarding the transforming resources, i.e. production facilities and machinery, concern all lifecycle phases. New equipment acquisition or equipment upgrades entail normally large investments, and maintenance contributes by providing knowledge on the status of plant machinery, and information on historical reliability and expected reliability, spare parts conditions and availability. During the acquisition phase, and even during the production line design and configuration phase, some case companies involve maintenance function (C1, C3, E2). This involvement implies analysing through-life maintenance costs, providing actual data on reliability based on current machinery operations, and suggesting adequate failure rate and useful life expectancy figures as machine specifications.

“If I design a new plant and I do not involve maintenance I make the mistake, that we said before, for example, of neglecting the maintenance costs in the investment. I can make a selection of a plant or equipment seemingly convenient that has unacceptable maintenance costs” (MM, C3)

“Failure rate and useful life rate are ours; it is me that propose them [for equipment acquisition]” (MM, E2)

“For us, it is continuous to change layout, change raw materials. In this sense, maintenance function is necessary” (OM, C1)

In F1, maintenance participated in setting production lines along their ramp-up phase, e.g. setting the adequate equipment parameters during a line (re)-configuration in order to make a defined product in that line. In C2 and M1, maintenance is also involved in the assembly of machinery for the plant, due to their knowledge on machinery.

During the equipment use phase, and over the course of its lifetime, the equipment will face progressive degradation and more maintenance interventions are required to keep it in good working conditions (C1, T1); this may involve high investments on extraordinary maintenance interventions to extend the equipment lifetime (M1). All interviewees mentioned the ageing of the machinery as a source of

concerns: increased needs of maintenance interventions, higher operating costs, and lack of spare parts. The MM in C2 noted that continuing using old machinery might become more expensive than acquiring new ones, as providers may not have available spare parts or need to remake them specifically when out of catalogue and this increases their maintenance costs. This indicates difficulties related to obsolescence of equipment within production plants. Overall, maintenance function seems fundamental for conserving versus acquiring equipment decisions.

The way maintenance is performed influences equipment and spares lifetime. While providing adequate maintenance interventions can extend their useful life, performing poor maintenance could trigger failure mechanisms (C3) or increase spare parts usage, e.g. more frequent part substitution due to poor lubrication (T1). This can lead to earlier disposal and wasted lifetime, with subsequent environmental impacts. The MM in C3 specifically stated that adequate maintenance avoided asset material damage and contributed to asset integrity, being the asset integrity of significant importance in C3 operations. Asset integrity, a concept from the oil and gas industry, refers to equipment performing effectively while protecting people and the environment from foreseeable harm (Narayan 2012; Ratnayake and Liyanage 2009). It has not been explored in other industrial settings, thus bringing interesting opportunities for further research.

Regarding the end-of-life (EOL) of production lines and equipment, maintenance function participates in disassembling old machinery (C1, E2, M1). This creates opportunities for reuse of components and recovery of spare parts for old machinery.

“We dismantled a fully automated factory that failed. As they were going to throw it all away, we started to dismantle inverters, drives, etc., if there are good parts over there, we take them and we keep them” (MM, E2)

“I made a lot of plants using old machinery that was kept aside, and then we used them instead [as spare parts]. This [is done] maintaining the safety and regulatory measures, for example, on electrical systems this can rarely be done” (OM, C1)

“We may recover some equipment parts as spare parts. In some particularly old facilities, for some machines those are the spare parts then, so if there is a similar machine, we keep them” (MM, M1)

The TM in E1 mentions that they normally dispose old machinery; however, in the previous year they have started a registry of equipment within the machinery fleet of several plants. An employee from the centralised engineering function checks this registry every six months for updates on equipment that may be disposed soon and keeps this database alive to enable equipment sharing between plants, if a requirement for an unusual processing comes up. This shows a proactive approach to EOL of production lines and equipment.

Last but not least, production outcomes are also remarked in this environmental dimension. In fact, they are influenced by maintenance, in terms of obtaining a good quality in the final product (as discussed previously) and avoiding scrap generation. Scrap generation then wastes materials in the first place, but also incurs in additional extra consumption of utilities and consumables to create a substitute quality-compliant product. Similarly, additional resource consumption occurs during rework processes to address the non-quality.

“If the right maintenance is not done or maintenance is done poorly, there is a risk to produce scrap, anyway, there is a real risk to ruin the material” (TM, E1)

“A proper maintenance, for example, avoids that you rework a fabric because it has creases or stains. So, you have to rework and consume energy again, consume water again, you consume air again” (TM, T1)

E1 uses OEE analysis to understand why waste is being produced and how to improve their processes and machines to produce less waste, including revising how machines

are being maintained. The TM shares that rework of non-quality outcomes was recently implemented and observes twofold benefits:

“First of all, you can see the quality of the scrap; if you repair and put again onto the cycle, the first effect is the decrease of quantity of scrap, and it is an important decrease. Another one, and the more interesting effect, is that creates awareness. If a worker decides that something is scrap it doesn't have any consequence for him/her, he/she puts it in a box and it is not anymore him/her problem, but if he/she has to take the box and evaluate all pieces there, and repair if possible... Then he/she really starts worrying not to have scrap and not to have to rework”. (TM, E1).

4.3.1 Summary of findings and remarks

Our findings demonstrate that maintenance has a manifold influence on environmental aspects of production processes, assets and facilities.

Machinery working out of ideal conditions implies higher resource consumption and a reduction in expected tolerance of input material in the production process. Additionally, performing maintenance interventions promptly and following an adequate protocol can reduce scrap generation and reduce resources needed for rework, and can also have a positive impact even on land, biodiversity and natural habitat conservation when performed outdoors.

The findings also confirmed the enlarging scope of maintenance responsibility along the whole lifecycle of production assets and other plant facilities. In this regard, we provide empirical evidence of maintenance contribution to new equipment acquisition or upgrade decisions, to the setting up of production lines, and to ensuring asset integrity. A proactive approach to asset EOL is also enabled by seeking opportunities for reuse and recovery of components, creating a pool for intra-organisational sharing of equipment, and effectively extending the life of assets and spares. This aligns with the envisaged role of maintenance suggested by Diallo et al.

(2017) on remanufactured and second-hand products to adapt maintenance approaches based on their usage history and the EOL process.

Further, we have uncovered strong links between the maintenance function and energy management and observed different levels of involvement in energy management activities in the analysed maintenance functions. These empirical findings support the instances described by Ball and Lunt (2018b) on the potential adequacy of maintenance to provide technical support to energy management, and show instances of maintenance engagement beyond a supporting role. Due to the novelty of these findings, they represent a highly interesting area for further research.

4.4 Social dimension of maintenance

Results related to this dimension are particularly interesting, as it is often the least discussed in manufacturing studies (Eslami et al. 2018). The section presents findings related to teamwork and engagement of maintenance personnel within the maintenance function and with other plant functions. It includes aspects of occupational health and safety, and community and external stakeholder relations of maintenance. It is worth noting that diversity aspects did not emerge during the interviews or the data analysis.

Most case companies have undertaken initiatives to widen the maintenance communication and collaboration to other plant functions. They report success examples of joint work with R&D, labs, technical office and plant engineering on the configuration and development of adequate production processes for new products, and within this, maintenance personnel have been able to propose suggestions to product design (E1, A1). In E2, discussions on specific modifications to the equipment are frequently held, as the MM contributes to the preparation of specifications for equipment acquisition.

Most interviewees reported a collaborative approach with production and quality, and only few suggested some concerns and tensions related to interventions or resources. The relationship with production is longstanding and joint decisions are common (E1, C2), although production is sometimes seen as a client of maintenance (C2, E2, A1, M1). Most companies see the relationship with quality in a more positive manner. The TM in E1 mentions that quality and maintenance are so interlinked that they need to jointly discuss and approve any change to maintenance plans implying the removal of preventive maintenance interventions, due to potential quality risks. There is also a good relation with HR to develop adequate training for maintenance personnel (E1, C2, M1). This is especially relevant for new acquired technologies that maintenance personnel should be adequately trained on, to keep them in good working conditions (E1, C3).

“Innovation brings the introduction of new technologies that have to be maintained, the new processes have to be maintained. Thus, wherever innovation brings new processes, it happens to talk about empowerment of maintenance personnel” (TM, E1)

The collaboration with the health and safety function was often mentioned in relation to technical contributions to working groups on these areas, to the development of operating and safety plant procedures, and to defining interventions to face anomalies and risks (E1, C2, C3, M1, F1). Preventive maintenance is essential in areas with hazardous materials to avoid health-related risks.

"Since we are the operating arm, we are heavily involved on all work groups [for safety and environmental certifications], together with the HSE [Health, Safety and Environment] office" (MM, M1).

“The area where we have chemicals that are dangerous, obviously here all preventive maintenance needs to be done and if not, the risk for others’ health is very very important” (TM, E1)

In C2, maintenance is also recognised for its contribution to certification processes, i.e. providing inputs to the development of relevant procedures, and for being an area that it is thoroughly checked during audits. The maintenance team is also in charge of safety interventions related to fire protection and prevention of major incidents (emergency team 24h) in M1.

The contribution of maintenance to occupational health and safety regards directly the following (C1, E1, E2, F1): the prevention of safety issues from happening by performing preventive maintenance, the prompt response in case a safety issue emerges in the plant, the performance of maintenance interventions adequately, without incidents, and finally the restoration of safe working conditions after the maintenance intervention. The latter can affect even the healthiness of the product when it requires certain hygienic operating conditions for machinery.

“More easily we tend to forget it [restoration of a safe condition after an intervention] and really there is a risk of harming people, so this is a theme that we are doing very important campaigns on” (TM, E1)

“A maintenance intervention done well ends up with the machine clean, it does not end with the machine dirty, it is essential” (OM, F1).

"This leads us to have suppliers that are aware of this [safety behaviour while performing interventions]" (OM, C1)

The collaborative environment, in which maintenance currently operates in some companies, has reduced pressure in the working environment for maintenance personnel. For example, in C1 increasing engagement and collaboration with other plant functions has created better understanding of maintenance timings and effectiveness. For example, it has reduced the instances in which maintenance is reprimanded when not able to perform an unexpected corrective intervention immediately. C2 has made a shift towards more proactive maintenance interventions that reduced failures and

downtime and caused a reduction of pressure on the maintenance personnel and ability to work without spending overtime hours.

In E1, empowerment through training and career development opportunities for maintenance personnel contribute to create an open environment, rather than seeing maintenance function as a silo and without promotion possibilities (as it has traditionally been). Providing opportunities for career promotion and interactions with managers to suggest improvement ideas contribute to the good working environment in E1 and C2. Moreover, small investments in new tools for maintenance personnel have also a positive effect, considered much bigger than their costs by the MM in C2, who observed afterwards improvements on work accuracy and motivation.

External stakeholders of maintenance function were also discussed during the interviews. The most commonly mentioned were suppliers and equipment manufacturers (C1, C2, C3, E1), certification bodies (C2, M1), and firefighters (C2, M1). Third parties perform some maintenance interventions, requiring specialised knowledge. These providers are requested to comply with safety standards and behaviour and they are often managed directly by maintenance function. The TM in E1 sees the relationship with equipment manufacturers and spare part suppliers as a key one and mentions their willingness to establish collaborative relations with those that show proactivity in terms of co-design, improvement suggestions. Two companies work closely with firefighters that provide training activities and emergency courses to plant personnel and make regulatory verifications on their facilities. In C2 facilities, the firefighters do their own training; in case of emergency they already know the plant and could enable faster interventions, the MM explains.

Finally, M1 is located within the urban area. This makes them to have a greater connection with the community. From a maintenance perspective, they have trainees from schools and they emphasize on hiring third parties mainly from the region.

4.4.1 Summary of findings and remarks

Findings related to this social dimension illustrate the collaborative environment in which maintenance operates in most of these companies, and the achieved benefits on reducing pressure in the working environment, training on new plant technologies, career development opportunities, and higher work accuracy and motivation of maintenance personnel. Fluent communication and collaboration with other business functions led to better understanding of maintenance timings and effectiveness.

Within the spectrum of cases investigated, we uncovered collaborative relations of maintenance with other plant functions, i.e. production, quality, HR, health and safety, R&D, labs, technical office and plant engineering. Although not present in all companies, these need to be taken as instances of the potential advantages when maintenance collaborates with other plant functions. The relation with production function was reported in a positive manner in most companies; only a few suggested some concerns and tensions. Analysis of synergies and challenges between maintenance and production functions are often presented in literature. For example, Tonke and Grunow (2018) studied the integration of production and maintenance plans, by scheduling shutdowns during periods of overcapacity to reduce wear and tear on equipment, and Muchiri et al. (2014) highlighted the need of combining knowledge of operating and maintenance practices for asset performance analysis and optimisation. Better joint models of maintenance planning and production scheduling can help achieve higher robustness and stability in the production system (Paprocka 2019).

Contributions to relationships and fulfilment of expectations with external stakeholders strengthen the consideration of maintenance as a value-adding business function beyond the boundaries of the production system (Söderholm et al. 2007). Eventually, examples of fruitful relations with external stakeholders are also identified in this study, e.g. good understanding and engagement with certification bodies, equipment and spare parts suppliers, and the local community.

5. Discussion and conclusions

This exploratory research has uncovered a range of impacts and contributions, illustrating that advanced practice in maintenance contributes to sustainability in manufacturing. Insights derive from nine manufacturing companies selected as exemplars of maintenance as a value-adding function, where maintenance plays a key role in achieving business strategy. This suggests a coherent functional strategy serving as a vital engine for the business (Martin and Riel 2019). Therefore, and confirming observations elsewhere, our data shows that well-managed and well-performed maintenance can be utilised to contribute to business strategy. This research seeks to go further and to identify how these exemplary maintenance practitioners impact and contribute to sustainability in manufacturing companies.

The exemplary nature of these cases implies that findings may not be valid for mainstream manufacturing companies, but we argue that the findings do hold the potential to act as good practices that others could implement to improve their maintenance functions capabilities and overall sustainability. Observed practices that achieved positive results in these companies are the following:

- Involving maintenance in all stages of production system and assets lifecycle management to leverage on relevant maintenance information and knowledge.

This has resulted in avoided material waste in production, preserved asset integrity, and increased material / component reuse and recovery at the EOL;

- Categorising maintenance budget entries based on the outcome obtained from the intervention. This has reinforced the visibility of maintenance respect to safety, resource savings, and product quality;
- Using maintenance techniques and methods in non-traditional maintenance areas, e.g. using OEE analysis to identify sources of waste in production, using failure analysis techniques to investigate energy inefficiencies, and using RCA to analyse non-quality instances in final products related to consumer complaints;
- Conducting improvement maintenance interventions. This has increased resource efficiency, enhanced assets reliability, maintainability, safety, and prevented misuse in operation;
- Introducing formal responsibilities for energy management within the scope of maintenance function and creating synergies between maintenance techniques and intervention planning, and energy auditing and analysis. This has resulted in energy savings and improvements in energy management;
- Keeping an updated equipment registry between production plants belonging to the same organisation with the objective of identifying potential intra-organisational reuse of those about to be disposed or discarded due to changing production needs. This enabled higher equipment utilisation and delayed disposal;
- Creating a collaborative and open working environment in maintenance function. This has led to less pressure, more empowerment of maintenance

personnel and more cross-functional improvements for production assets, their operation, and final products.

The findings of this study can inform senior managers about those maintenance actions that lead to a more central role of maintenance in enhancing sustainability performance. We provide instances of maintenance contributions within the main components of sustainability assessments in manufacturing organisations identified by Eslami et al. (2020): hierarchical manufacturing levels (i.e. product, process and system), product life cycle stages, and TBL dimensions. Particularly, these findings can help practitioners understand the potential value-adding role of the MM in modern manufacturing companies, analyse their main TBL impacts and devise a set of specific actions adequate for their own business and operational context. The findings can also help senior managers to reinterpret their approach to maintenance interventions and discover new ways of achieving more sustainable performances through preventive and improvement maintenance. Based on this analysis, we particularly propose the following steps to improve sustainability in production plants based on the uncovered maintenance-related contributions:

1. analyse key areas of maintenance impact on all sustainability dimensions within the production system;
2. establish a cross-functional team, which includes personnel from maintenance function, to identify solutions and improvements in all defined relevant areas for sustainability performance;
3. define a proactive approach to maintenance interventions based on preventive and improvement maintenance that address the relevant impact areas;
4. identify maintenance techniques, data and knowledge that can support the implementation of those sustainability-oriented solutions and improvements;

5. create mechanisms to support a cross-functional and collaborative working environment that focus on identifying solutions rather than each business function tackling problems in isolation.

The specific academic contributions of this work include: (1) building a comprehensive and empirically informed overview of maintenance impacts and contributions to sustainability; (2) providing empirical evidence of the transition of maintenance towards a value-added function in manufacturing companies and insights on how some exemplary cases have made it happen, and (3) bringing to light some unexpected connections between maintenance and final product competitiveness, and energy management. These two emerging connections deserve further investigation and are considered key areas for future research.

This work presents a holistic view of impacts and contributions of maintenance function, covering a wide range of economic, environmental and social aspects. This type of systemic study, simultaneously addressing the three TBL dimensions, is still unusual in the sustainable manufacturing field. The literature review done by Eslami et al. (2018) builds an outlook of the TBL sub-dimensions covered in studies of sustainability in manufacturing. Comparing our findings to these identified TBL sub-dimensions, we found instances where the maintenance function clearly contributes to them. Note that transportation (within environmental sub-dimensions) and logistics costs (within economic sub-dimensions) have not been covered here, due to the specific focus on maintenance function. Apart from these, the carbon footprint (within environmental sub-dimensions) and human rights (within social sub-dimensions) aspects did not emerge from our data analysis. In this direction, further work could build on our findings and analyse the carbon footprint of maintenance operations.

Regarding social sustainability aspects, further work can be done to explore aspects not covered within the current work, e.g. equality and diversity and human rights considerations in maintenance function, in different locations and operational settings. Other suggestions for future research regard the advancement of performance measurement systems to cope with the wide range of uncovered maintenance impacts and contributions, and the opportunity to explore the concept of asset integrity outside the oil and gas sector, as a driver for more responsible and sustainable asset management practices.

Due to the exploratory nature of this study, a multi-sector sample of nine case companies was used. This serves the purpose of gaining deep insights on the subject of study; based on rich qualitative empirical data we have drawn conclusions and increased the understanding on maintenance function impacts and contributions. Case study method is stronger on interpretation rather than generalisability (Stake 1995). While the prior is the main strength of this multi-case study, the latter constitutes its main limitation. Thus, further research is envisaged to overcome this in two ways: firstly, by developing a large-scale survey to extend the coverage of participating companies and identify links between maintenance maturity levels and sustainability improvements; secondly, by conducting in-depth studies to gather fine-grained insights of maintenance function's impacts and contributions to sustainability in a particular manufacturing sector.

Additionally, further research could explore the use of maintenance engineering techniques and methods outside the traditional scope of maintenance function (few instances are presented above) and the role of maintenance in emerging sustainability frameworks, e.g. cradle-to-cradle, PSS, 6R (Reduce, Reuse, Recycle, Recover,

Redesign, Remanufacture) and CE. These constitute promising lines of interdisciplinary research for maintenance and sustainability scholars.

Finally, yet importantly, further research could investigate how our findings can enrich ongoing developments of technological innovations in maintenance within the scope of Industry 4.0. Details on the environmental and social dimensions of maintenance complement extant approaches, such as lifecycle maintenance, e-maintenance and intelligent prognostics tools (Takata et al. 2004; Levrat et al. 2008, Lee et al. 2006). Our findings can be particularly relevant for the Prognostics and Health Management (PHM) body of knowledge in developing predictive maintenance approaches with overall benefits along the asset lifecycle (Sun et al. 2012; Guillen et al. 2016; Fumagalli et al. 2019). More holistically, our findings can inspire smart / intelligent maintenance strategies to pursue TBL outcomes in an explicit manner, thus strengthening the sustainability agenda in advances towards smart production systems.

This work demonstrates that advanced practice in maintenance can play a role in achieving more competitive, responsible and sustainable performance in manufacturing companies. This is supported by the empirical evidence of our findings, e.g. the observations of an early shift of maintenance responsibilities toward energy management to leverage on maintenance expertise. Therefore, we believe that maintenance function needs to be taken more into consideration, and given a more central role in future research and practice addressing sustainability in manufacturing.

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Table 1. Overview of case companies’ characteristics and interviewees’ job positions.

Case	Sector	Plant size ¹	Market type ²	Competitive priorities ³	Product complexity ⁴	Maintenance Maturity Level ⁵	Interviewees (Job position)
A1	Automotive	101-1000	B2B	Quality, cost and delivery punctuality	V: Low C: High	ML4-high; Higher than sectorial average (ML3-high)	Plant Operations Manager
C1	Chemical	up to 100	B2B	Quality, flexibility, product innovation, and customer service	V: High C: High	ML3-low; Same as sectorial average	Plant Operations Manager
C2	Chemical	Above 1001	B2B	Quality and customer service	V: Low C: Low	ML3-low; Same as sectorial average	Plant Maintenance Manager
C3	Chemical	up to 100	B2B	Quality, key partnerships and product innovation	V: Low C: High	ML4-high; Higher than sectorial average (ML3-low)	Corporate Maintenance and Technical Manager
E1	Electric & Electronic	101-1000	B2C	Quality, cost and product innovation	V: Low C: Low	ML3-high; Higher than sectorial average (ML3-low)	Plant Technical Manager
E2	Electric & Electronic	101-1000	B2C	Quality and delivery punctuality	V: Low C: Low	ML3-high; Higher than sectorial	Plant Maintenance Manager

						average (ML3-low)	
F1	Food & Beverage	101-1000	B2C	Quality, cost and product innovation	V: High C: Low	ML4-high; Higher than sectorial average (ML3-low)	Corporate Operations Manager
M1	Metal	Above 1001	B2B	Quality and know-how	V: Low C: High	ML2-high; Same as sectorial average	Plant Maintenance Manager
T1	Textiles & Clothing	up to 100	B2B	Quality, delivery punctuality and product innovation	V: High C: High	ML3-high; Higher than sectorial average (ML2-high)	Plant Technical Manager

¹ Plant size defined in three ranges: up to 100, 101-1000, above 1000 employees; ²

Market type defined as business-to-business (B2B) or business-to-customer (B2C); ³

Competitive priorities based on documentation, interviews and TeSeM survey

questionnaire; ⁴ Product complexity aspects considered are variety (V) and

customisation (C); ⁵ Based on results from TeSeM survey on maturity of maintenance functions.

Table 2. Hidden costs of maintenance function.

Hidden costs	Exemplary quotes
Rework	<i>“A proper maintenance, for example, avoids that you have to rework a fabric because it has creases or stains [...] Indirectly, a proper maintenance prevents further additional costs”</i> (TM, T1)
Opportunity costs, associated with not serving product demand	<i>“Since our products often have a relation one-to-one with the production lines, that is, one production line makes one product, not always but generally speaking, then the market goes straight on the production line”</i> (OM, F1) <i>“Complete on time regards reliability, I need to have reliable plants”</i> (MM, E2)
Process inefficiency	<i>“The challenge of this type of products [commodities] is to reduce the performance losses, in this, maintenance is also involved”</i> (OM, A1)
Non-optimum transformation of materials	<i>“I make a periodic preventive check on the pump because if not, I will ruin the product”</i> (OM, C1) <i>“If the machinery is well-maintained, automatically also the raw material is transformed in an optimal manner”</i> (TM, T1)
Non-quality complaints	<i>“Not doing preventive maintenance activities could generate non-quality of the product and, as a consequence, this non-quality could reach the customer”</i> (TM, E1) <i>“If the machines are not well set, they do it wrong, originating customer complaints. So the machines have to be maintained and always in perfect reliability conditions”</i> (MM, E2)
Dealing with bad suppliers	The MM in C2 mentioned that having good suppliers is seen as a contribution to having good maintenance service; however, managing bad suppliers incur in high hidden costs emerging from difficult / non-collaborative relationship, lack of supply or technical quality.