A CONCEPTUAL FRAMEWORK FOR MEASURING MAINTENANCE IMPACTS ON SUSTAINABILITY

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A CONCEPTUAL FRAMEWORK FOR MEASURING MAINTENANCE IMPACTS ON SUSTAINABILITY

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Alla mia tenace e dolce mamma,
al mio riservato e unico papà,
che ne sarebbero stati fieri.

Con amore.

"If you can't fly, run.
If you can't run, walk.
If you can't walk, crawl.
But by all means, keep moving."

[Martin Luther King]

Table of content

List of Figures

List of Tables

Abstract

The paradigm of sustainable manufacturing has attracted a great deal of attention over the last decade as an emerging manufacturing approach intending to empower the enterprises to cope with several challenges (such as depletion of physical resources, stricter laws and regulations, economic stagnation, and customer request for higher product quality) and guide them to stand out in today's competitive environment. Sustainable manufacturing is defined as creation of manufactured goods through the use of a series of processes that minimise the negative environmental impacts, conserve energy and natural resources, are safe for employees, communities and consumers, and are economically sound.

In such today's competitive industrial context, maintenance process is major lever of organisation efficiency. Indeed, maintenance provides company the ability to keep its production system in efficient state and able to provide product at the required quality. In that way, maintenance process has a large potential in pursuit of sustainable manufacturing thanks to its impact on other company's processes. In fact, maintenance affects production volume and costs, asset performance, equipment availability, quality of the final product, but also health and safety of people, the surrounding natural environment and the social welfare. Maintenance has many direct and indirect impacts on sustainability-related aspects and a proper and sustainable management of maintenance processes lead to reduce and control such impacts. A sustainable maintenance management strives for more efficient resource and energy management, for reduction of wastes associated to maintenance, elimination of negative environmental impact, and guarantee of employees and stakeholders' safety.

Despite of the increasing attention on the aforementioned area of investigation in very recent years, an exhaustive and detailed literature review related to 'maintenance and sustainability in industrial context' was not found. For this reason, the current state of the art was investigated in order to provide an overview of the literature in 'maintenance and sustainability'. The review was conducted through a scoping literature review methodology that, differently from conventional reviews based on the author knowledge perspective, follows a protocol minimizing the subjectivity. The main information was extracted and gaps were identified.

First, the literature review underlined the research challenge of better investigating and defining maintenance impacts on economic, environmental, and social sustainability. Therefore, the relationships between maintenance processes and sustainability indicators should be defined and formalised. A sustainable maintenance management should

reduce maintenance impacts and their consequences, and new frameworks/methodologies/models should be defined in order to guide the stakeholders to reduce economic, environmental and social impacts associated with industrial maintenance activities.

A conceptual framework for measuring maintenance impacts on sustainability was then developed and provided in the thesis as scientific contribution to the research challenge identified and reported above. Therefore, maintenance impacts on sustainability and the relationships between sustainability indicators and maintenance processes were identified. The developed framework can guide and help several stakeholders to define maintenance direct and indirect impacts on sustainability aspects, to select the indicators of interest for measuring such impacts, and to be more aware about maintenance and sustainability relationship.

The framework was then validated through a pilot survey study conducted to reach such goal. In particular, an ad hoc defined interview was submitted to several stakeholders of different industrial contexts and the main results allowed validating the content of the framework. Contextually, the spread of measurement of maintenance impacts on sustainability in industrial field was unveiled.

The main contributions of this research can therefore be summarised as:

- the definition of the concept of 'sustainable maintenance';
- the development of a scoping literature review in the research area of 'maintenance and sustainability in industrial context';
- the identification of gaps and research challenges in the research area;
- the identification of maintenance impacts in the organisation up to the customer in the three pillars of sustainability through the definition and formalisation of sustainability indicators of different systems affected by maintenance processes;
- the development of a holistic conceptual framework for measuring maintenance impacts on sustainability, applicable to a wide range of industrial contexts;
- the development of a pilot survey study through the submission of an interview defined ad hoc for validating the content of the framework and for unveiling the current spread of measurement of maintenance impacts on sustainability in industries.

Introduction

This introductive section provides a short description of the area of investigation, the specific thesis objectives, and the thesis structure.

Area of investigation of the thesis

Maintenance definition, processes, and objectives

Terminology standard BS EN 13306: 2010 defines maintenance as the "combination of all technical, administrative and managerial actions during the life cycle of an item intended to retain it in, or restore it to, a state in which it can perform the required function". According to EN ISO 9001, maintenance is a process since it consists of organised, coordinated tasks using resources and performed by various stakeholders to obtain a given result. Only recently, the EN 17007:2017 defined the maintenance processes with their description and characteristics, classifying them in three main families: management process, realisation processes (composed of four processes), and support processes (composed of eleven processes) (Figure 1). While the realisation processes contribute directly to achieve the expected result and must ensure that the needs expressed by the customer are satisfied, the support processes are essential to the functioning of the other processes, as they provide them the necessary resources. Instead, the management process must ensure the coherence of the realisation and support processes. The EN 17007 provides the overall mapping of maintenance processes, interconnected with each other (Figure 1).

Therefore, the huge importance of maintenance in industrial context, as function and as a set of processes, led to consider it not only as a supporting process to the productive one, but as a key function to create added value sustaining long-term profitability of an organisation.

The main maintenance objectives are (1) ensure plant functionality, (2) system life, (3) plant and environmental safety, (4) cost effectiveness in maintenance, (5) effective use of resources, and (6) human well-being (Dekker, 1996; Muchiri et al., 2011). These objectives already included some sustainability considerations, but researchers in maintenance field are still mainly focused on conventional aspects of maintenance, paying attention principally to technical and economic objectives.

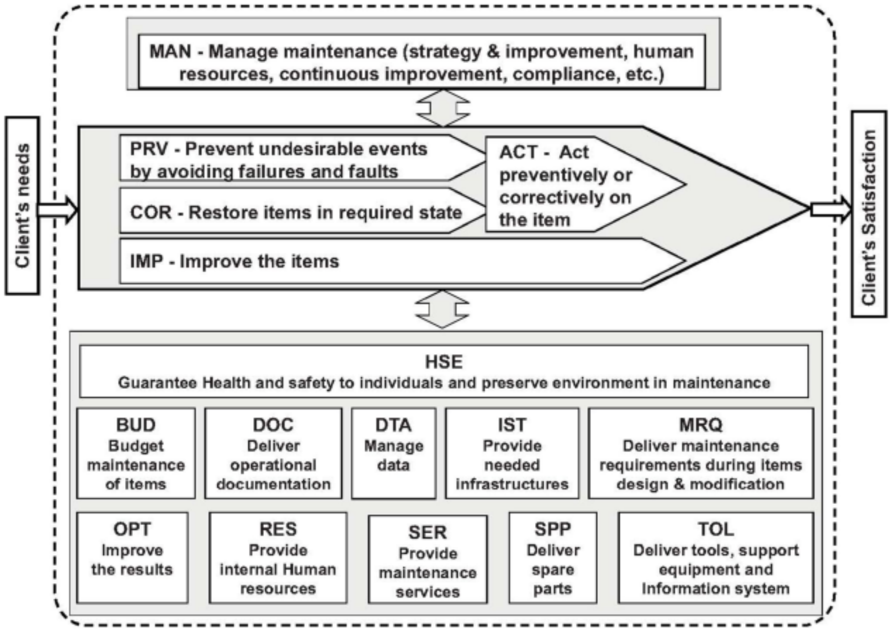

Figure 1 – *Overall mapping of maintenance processes (EN 17007: 2017)*

Maintenance and sustainability

Manufacturing companies face several challenges such as depletion of physical resources, stricter laws and regulations, economic stagnation, and customer request for higher product quality. The paradigm of sustainable manufacturing has attracted a great deal of attention over the last decade as an emerging manufacturing approach that intends to empower the enterprises to cope with these challenges and guide them to stand out in today's competitive environment (Chan et al., 2017; Chun and Bidanda, 2013; Eslami et al., 2018). Sustainability will be a crucial issue for the existing status and towards tomorrow, the driving force of the twenty-first century, leading sustainability requirements to be ubiquitous; the major drivers of sustainability are customers' requirements, governance and regulation, environmental priorities, the shortage of natural resources, and increasing energy costs (Garbie, 2013; 2014; 2015). Sustainable manufacturing is defined as creation of manufactured goods through the use of a series of processes that minimise the negative environmental impacts, conserve energy and natural resources, are safe for employees, communities and consumers, and are economically sound (Mani et al., 2014; Dubey et al., 2015; U.S. Department of Commerce, 2010). Toward such a goal, the assessment of the sustainability of organisations requires indicators to evaluate their journey toward the sustainable manufacturing. Such assessment should evaluate the impact of companies on economic, environmental, and social aspects (Harik et al., 2015). Well-defined performance indicators can help to achieve sustainability goals, identifying potential gaps between actual and desired sustainable performance of company departments. Such indicators can guide the stakeholders towards closing the gaps, focusing resources on specific processes and on the reduction of their impacts, in order to satisfy the fixed goals.

In such today's competitive industrial context, maintenance is major lever of organisation efficiency (Jasiulewicz-Kaczmarek, 2013). Indeed, maintenance provides companies the ability to keep its production system in efficient state and able to provide product at the required quality. In that way, maintenance process has a large potential in pursuit of sustainable manufacturing thanks to its impact on other company's processes (Franciosi et al., 2017; 2018). Maintenance contributes to promote sustainability through innovative management practices, the integration of sustainability goals into conventional maintenance management, the adoption of new measures, and the exploitation of potentials available form new enabling technologies (Garetti and Taisch, 2012; Iung and Levrat, 2014). Nevertheless, the role of maintenance as contributing to the sustainable operation has attracted more attention in research and practice fields only since the last few years.

Maintenance affects production volume and costs, asset performance, equipment availability, quality of the final product, but also health and safety of people, the surrounding natural environment and the social welfare (Franciosi et al., 2018; Jasiulewicz-Kaczmarek, 2013). In fact, maintenance has many direct and indirect impacts on sustainability-related aspects and a proper and sustainable management of maintenance processes lead to reduce and control such impacts. A sustainable maintenance management strives for more efficient resource and energy management, reduction of wastes associated to maintenance, elimination of negative environmental impact, and guarantee of employees, stakeholders safety (Jasiulewicz-Kaczmarek, 2014; Sari et al., 2015) and aims to achieve a dashboard in relation with sustainability.

In this context, maintenance function is not to be considered as only a service to repair and conserve equipment, but also as a wide process or series of activities that need to be managed in a sustainable perspective (Iung and Levrat, 2014).

In this thesis, Sustainable Maintenance is defined as "*a set of interconnected processes that, from one hand, have to sustain assets/equipment during their operation in order to guarantee the compliance of production process, of manufactured products and to reduce industrial impacts on economy, society, and surrounding environment and, on the other hand, itself has to be a sustainable business function in order to limit flows and impacts generated during maintenance activities*".

Thesis objectives

Despite of the increasing attention on the aforementioned area of investigation in very recent years, an exhaustive and detailed literature review related to 'maintenance and sustainability in industrial context' cannot be found. For this reason, the first objective of the thesis was to investigate the current state of the art and to provide an overview of the literature in 'maintenance and sustainability'. The review was conducted through a scoping literature review methodology that, differently from conventional reviews based on the author knowledge perspective, follows a protocol minimizing the subjectivity. The main information was extracted and the gaps were identified.

The detailed analysis of the papers sheds light on the research challenge of better investigating and defining maintenance impacts on economic, environmental, and social sustainability. Therefore, the relationships between maintenance processes and sustainability indicators should be defined and formalised. A sustainable maintenance management should reduce maintenance impacts and their consequences, and new frameworks/methodologies/models should be defined in order to guide the stakeholders to reduce economic, environmental and social impacts associated with industrial maintenance activities.

According to the research challenge reported above, the second objective of the thesis was to identify the maintenance impacts on sustainability through the identification of the relationships between sustainability indicators and maintenance processes. Such impacts can be direct through the execution of maintenance activities and indirect on production process and on the quality of the final product due to maintenance efficiency/inefficiency. A conceptual framework for measuring maintenance impacts on sustainability was then developed and provided as the main scientific contribution of this thesis. The developed framework can guide and help several stakeholders to define maintenance direct and indirect impacts on sustainability aspects, to select the indicators of interest for measuring such impacts, and to be more aware about maintenance and sustainability relationship.

Finally, the third objective of the thesis was to validate the framework and to unveil the spread of measurement of maintenance impacts on sustainability in industrial context. A pilot survey study was conducted to reach such goal through the submission of an ad hoc defined interview to several stakeholders of different industrial contexts.

Thesis structure

The thesis is structured in four chapters.

Chapter I provides a scoping literature review in the area of investigation of 'maintenance and sustainability' in industrial context. Moreover, the main gaps and research challenges are highlighted.

Chapter II presents the different steps adopted for designing the conceptual framework developed for measuring maintenance impacts on sustainability. Therefore, the dimensions and the elements of the framework, its content, its structure, and an explanation on how use it, were provided.

Chapter III provides a first step of validation of the framework and discusses the current spread of measurement of maintenance impacts on sustainability in industrial contexts. Therefore, the structure of the interview defined for the purpose, the sample of the analysed stakeholders, the data collection, and the main achieved results were presented.

Chapter IV discusses the main conclusions and contributions of the thesis. Suggestions for future research in the area of investigation of 'maintenance and sustainability' as provided as well.

Chapter I

I. State of the art, gaps and challenges for promoting sustainability through maintenance processes: a Scoping Literature Review

I.1 Introduction

Taking into account the social importance of industry and, in particular, of manufacturing in our society, while considering its huge impact on the environment due to energy and resource consumption, and released emissions, sustainable manufacturing can be considered as one of the most relevant issues to address for pursuing the big frame of sustainable development (Garetti and Taisch, 2012). The paradigm of sustainable manufacturing led to pay more attention on impacts that each organisational process could have on sustainable development. In fact, all the processes in manufacturing companies have significant roles in the assurance of 'sustainable' status of the industrial assets. In particular, in such today's competitive industrial context, maintenance is major lever of organisation efficiency (Jasiulewicz-Kaczmarek, 2013). Indeed, maintenance provides company the ability to keep its production system in efficient state and able to provide product at the required quality. In that way, maintenance process has a large potential for contributing to sustainable manufacturing thanks to its impact on other company's processes (Franciosi et al., 2017; 2018), becoming increasingly important compared to the past.

Moreover, poor maintenance quality and ill-defined maintenance practices lead to different problems and negative economic, environmental and social impacts such as, among all, hazardous emissions, production waste due to systems malfunctions, health and safety incidents, in-efficient energy use, in-effective resource and material consumption, financial losses due to capacity losses or downtime (Liyanage and Badurdenn, 2010; Raouf, 2009). Maintenance should contribute to the minimisation of environmental and social impacts of a company, the reduction of life cycle costs and enhancement of equipment durability and socioeconomic well-being (Afrinaldi et al., 2017).

A major contribution of maintenance function in the respect of sustainable systems is then expected. A sustainable maintenance management should contribute to the reduction of maintenance impacts on sustainability. Maintenance performance should be measured in order to evaluate the gap between the actual and desired sustainable performance and the disparate maintenance impacts on sustainability.

However, despite of the increasing attention on this research topic in very recent years, an exhaustive and detailed literature review related to 'maintenance and sustainability' in industrial context was not found. For this reason, the first Chapter of the thesis provides an overview of the literature in the area of investigation of 'maintenance and sustainability' in industrial context. The review was conducted through a 'scoping' literature review methodology that, differently from conventional reviews based on the author knowledge perspective, follows a protocol minimizing the subjectivity. In particular, being "Sustainable Maintenance" a wide and cross topic, a 'scoping' literature review methodology was conducted in order to widely investigate the current state of the art, to cluster research papers, to extract main information, and to identify possible gaps.

This chapter is organised as follows. Section I.2 presents the research method used for conducting the scoping literature review. Section I.3 reports the review results, while section I.4 provides a detailed discussion about the results with the identification of the research clusters. Finally, Section I.5 summarises the main issues and research challenges.

I.2 Methodology

A scoping study is a technique to 'map' relevant literature in a specific field of interest. Scoping studies might 'aim to map *rapidly* the key concepts underpinning a research area and the main sources and types of evidence available and can be undertaken as stand-alone projects in their own right, especially where an area is complex or has not been reviewed comprehensively before' (Mays *et al*. 2001, pp.194).

Differently from a systematic review, typically focused on a well-defined question where appropriate study designs can be identified in advance, a scoping study tends to address broader topics where many different study designs might be applicable (Arksey and O'Malley, 2005).

Generally speaking, a scoping study might be perceived either as one part of an ongoing process of reviewing, the ultimate aim of which is to produce a full systematic review, or it might be conceived as a method leading to the publication and dissemination of research findings and of the main research gaps identified in a particular field of enquiry (Arksey and O'Malley, 2005).

Another important distinction between scoping reviews and systematic reviews is that, unlike systematic reviews, scoping reviews provide an overview of the existing evidence, regardless of quality (Peters, Godfrey, Khalil et al., 2015). This is because, while systematic studies seek only the best available evidence to answer a specific question, scoping reviews aim to provide a map of what evidence has been produced. Hence, generally a formal assessment of methodological quality of the included studies of a scoping review is not performed (Peters, Godfrey, McInerney et al., 2015).

Consistently with the aforementioned definition, this study is classified as Scoping Literature Review (SLR) that, rather than being guided by a highly focussed research question, is guided by a requirement to identify all relevant literature, to provide a broad overview of the PhD topic, and to identify research gaps in the existing literature. In particular, the objective of this SLR (Franciosi et al., 2018) is to identify and to examine peer-reviewed papers that presented evidence on the relationship between maintenance and sustainability in the industrial field.

In that way, the addressed research questions were:
RQ1. What is known from the existing literature about the role of maintenance for industrial sustainability?
RQ2. What are the main approaches/methodologies/frameworks/tools developed to date concerning this topic?
RQ3. How “maintenance 4.0” can contribute to sustainable development? In other words, how the enabling technologies 4.0 can contribute to sustainability of maintenance process and of organisations?

The SLR was carried out through a well-defined methodology, structured in different steps discussed in detail in the following sub-sections.

I.2.1 Identification of research databases and keywords definition

Searches were conducted using two scientific databases: Scopus and Web of Science.

A set of keywords, structured in three different groups, was elicited for these databases and presented in Table I.2.1. Group A includes keywords related to maintenance field; Group B is composed by keywords related to sustainability field; Group C introduces the keywords related to the industrial and manufacturing fields to contextualize the search. Moreover, considering the increasing pressure towards the Industry 4.0 era, keywords ‘4.0’ and “smart factory” were included in Group C.
These represent the main keywords coherently with the SLR objective but, obviously, each group can be extended. For example, the keyword “green” could be included in Group B in a further step of the SLR to evaluate the papers including the compound keywords such as ‘green maintenance’ or ‘green manufacturing’.
The keywords that needed to be searched together were included in the groups with the inverted commas (e.g. “asset management”). To obtain the final keywords list used to search, the keywords of each group are linked with the Boolean Operator OR, while the groups are linked each other with the Boolean Operator AND to make the relationship among groups.

Table I.2.1 - *Groups of keywords*

Group A	Group B	Group C
Maintenance	Sustainability	Industry
"Asset Management"	Sustainable	Industrial
	"Circular Economy"	Manufacturing
	"Life Cycle Assessment"	"Smart Factory"
		4.0

I.2.2 Literature search and paper selection through specific inclusion and exclusion criteria

The first step aimed to extract papers from the selected databases.

The search in the electronic databases took place in September 2017.

Papers that had the searched keywords in their title or abstract or keywords were screened.

The search was not limited to a specific year range.

Moreover, only articles in English and published in peer-reviewed journals, conferences or books were considered.

After running the search on the two databases, all papers were uploaded into a database manager (i.e., Mendeley) and all duplicates were removed.

The second step aimed to select relevant papers.

The selection process was divided into two phases.

The first selection phase involved the reading of the title, abstract, and keywords. In this screening phase, papers were classified as included, and excluded according to the specific Exclusion Criteria (EC) described below:

1st EC - Entire conference proceedings;

2nd EC - Papers do not establish a link between maintenance and sustainability in industrial field, or it is a secondary aspect than the main purpose of the paper;

3rd EC - Papers in which maintenance is a secondary aspect compared to the main purpose of the paper;

4th EC - Papers in which the sustainability goal is a secondary aspect compared to the main purpose of the paper.

The second selection phase included the reading of the full text of the papers selected in the previous stage and therefore a definitive assessment based on the 2nd, 3rd, and 4th exclusion criteria. If no full-text of the papers selected at the first screening phase was found, the related paper was excluded.

Finally, the “snowball” analysis was conducted through references scanning on the papers selected at the second stage in order to identify additional papers, suitable for the SLR goal. In other words, references of each selected paper were analysed with the aim of extracting additional papers coherent with the literature review scope and objective. However, these additional papers did not come out directly from the search in the electronic databases with the combination of the keywords listed in Table I.2.1.

An Excel work spreadsheet allowed us easily managing the step listed above and to have a final clear vision of the papers chosen after the second selection phase.

I.2.3 Analysis process and information extraction strategy

Each selected paper was analysed and then methodologically and conceptually classified based on two criteria (Table I.2.2) allowing us to more easily discuss the SLR results and identify research gaps.

The two aforementioned criteria are related to the type of innovative contribution that each paper provides to the literature and to the research method used to reach the research paper goals (Di Pasquale et al., 2017).

Table I.2.2 - *Types of Contribution and Research Method*

CONTRIBUTION	RESEARCH METHOD
C1. Development of method/ methodology/ model	R1. Case study
C2. State of the art	R2. Theoretical research/ Literature review
C3. Proposition of theoretical framework	R3. Experiental research/ Simulation
C4. Development of tool	R4. Other type of research method
C5. Other type of contribution	R5. Combination of research methods

Furthermore, the analysis was performed in an iterative way extracting the main information provided by papers that allowed us to identify research clusters in the scope of ‘sustainable maintenance’ in industrial context. In particular, through the reading of the selected papers and the identification of their main purpose, proposals, results and insights, it was possible to clearly identify different precise topics in the scope of interest. The aforementioned topics gave rise to research clusters, that were detailed with the definition of their content, therefore of the specific pertaining papers aggregated according to the cluster’s topic. In a logical way, these topics are addressing five interdependent questions, going in depth in the three research questions previously presented in section I.2:

- Does maintenance have an important role in sustainable development?
- If this role is important, how maintenance really impacts each of the three pillars of sustainable development?
- What are the maintenance models/methodologies/tools needed to control the targeted impact/performance of maintenance on the three pillars?
- How can these impacts be measured (by means of indicators) to ensure that sustainability performance is controlled?
- How the new technologies introduced by Industry 4.0 paradigm can change the role of maintenance in sustainable development?

All the information pertinent to the research questions and present in each paper were extracted and reported in the specific worksheet (see Section I.2.2) to allow us a detailed assessment of current state-of-the-art and of SLR results.

I.3 Results

Figure I.3.1 reports the Scoping Literature Review process.

The total number of papers resulted from the two databases search was 3007. After the duplicates scanning, 577 duplicates were found, for a total number of 2430 paper to analyse. After the first screening phase, 156 papers were identified as relevant. Among them 68 papers were selected (15 of 68 papers came from the snowball analysis) following the guideline reported in Section I.2.

As shown in Figure I.3.2, 40% of the selected papers are published on journals, 56 % in conference proceedings, and 4% are book chapters.

Since "sustainable maintenance" is a wide and cross topic, different types of journals are involved. However, the SLR has highlighted that a peak of publications in Journal of Cleaner Production occurs (Figure I.3.3).

More interesting is the classification of the conferences in which the papers selected in the SLR were published. In particular, 34% of these conferences belong to "production engineering research" category (e.g. Procedia CIRP) and 32% belong to "control and system engineering" category (e.g. IFAC – International Federation of Automatic Control - conferences). The remaining conferences belong to miscellaneous categories.

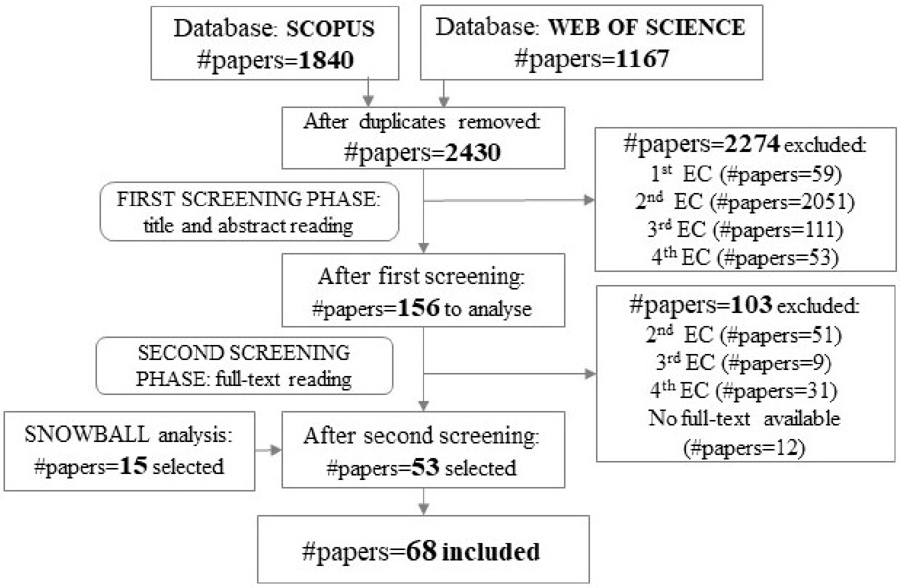

Figure I.3.1 – *Scoping literature review process*

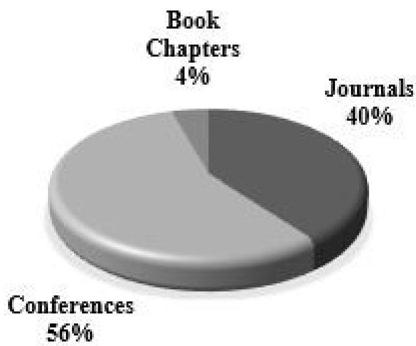

Figure I.3.2 - Editorial classification of selected papers

Figure I.3.4 reports the publication distribution over the years. Of the 68 papers selected in the SLR, 53 of them (78%) were published from 2012, highlighting a growing research interest in the “sustainable maintenance” field in the last 5 years.

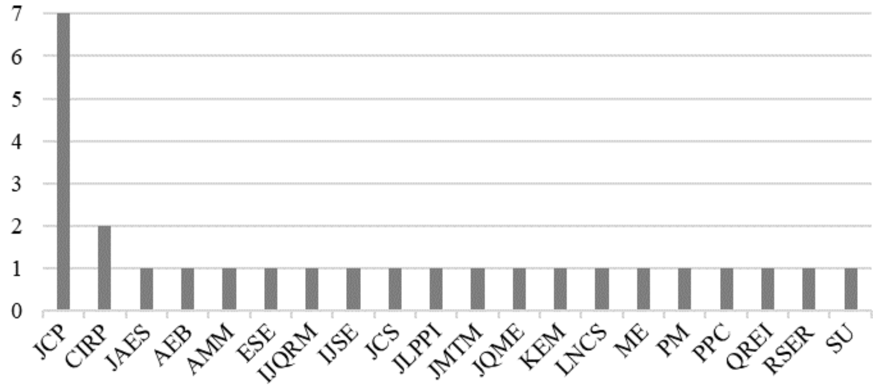

Figure I.3.3 - Number of papers per journal

Acronyms: JCP-Journal of Cleaner Production/ CIRP-CIRP Annals/ JAES-Journal of Applied Engineering Science/ AEB- Advanced environmental biology/ AMM- Applied Mechanics and Materials/ ESE- Environmental Science and Engineering/ IJQRM-International Journal of Quality and Reliability Management/ IJSE-International Journal of Sustainable Engineering/ JCS-Journal of Computational Science/ JLPPI-Journal of Loss Prevention in the Process Industries/ JMTM-Journal of Manufacturing Technology Management/ JQME-Journal of Quality in Maintenance Engineering/ KEM- Key Engineering Materials/ LNCS-Lecture Notes in Computer Science/ ME-Metalurgija/ PM- Procedia Manufacturing/ PPC-Production Planning & Control/ QREI-Quality and Reliability Engineering International/ RSER-Renewable & Sustainable Energy Reviews/ SU-Sustainability.

According to Section I.2.3, the 68 papers were classified compared to the type of contribution and the used research method, as shown in Table I.3.1. Concerning the type of contribution, 29 papers (42.6%) developed methodologies, methods or models; 19 papers (28%) proposed a qualitative/theoretical framework; 7 papers (10.3%) proposed a tool; and 1 paper is a state-of-the-art (1.5%). 12 papers (17.6%) belong to class C5 because they applied existing methodologies or they do not belong to other contribution classes.

Concerning the method used to carried out the research, 31% used case study, 26.5% theoretical research or literature review, 6% combination of two research methods and only 1 paper (1.5%) used an experimental research. 24 papers (35%) belong to R4 class since they do not present previous research method (e.g. papers using surveys as method).

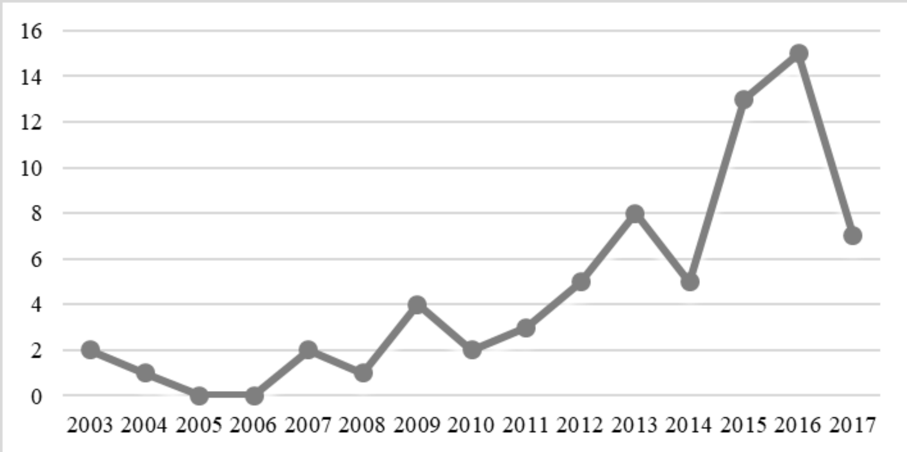

Figure I.3.4 - Publication trend by year

Table I.3.1 - *Paper classification in respect of type of contribution and research method*

CONTRIBUTION	# paper	RESEARCH METHOD	# paper
C1. Development of method/ methodology/ model	29	R1. Case study	21
C2. State of the art	1	R2. Theoretical research/ Literature review	18
C3. Proposition of theoretical framework	19	R3. Experiental research/ Simulation	1
C4. Development of tool	7	R4. Other type of research method	24
C5. Other type of contribution	12	R5. Combination of research methods	4
TOTAL	68	TOTAL	68

Each type of contribution is going to be discussed in detail in the following Section I.4.

I.4 Results discussion: identification of research clusters

The SLR results underlined different discussion topics. In particular, through the extracted information from the selected literature, it was possible to analyse it according to specific thematic areas that allowed us to identify and create research clusters in the field of interest (Figure I.4.1). These five research clusters were identified in order to take into account the main aspects addressed by researchers in the area of investigation of 'maintenance and sustainability in industrial context'.

In other words, the first cluster involves all the papers discussing in a general and descriptive way about the role of maintenance for contributing to the sustainability of production companies. The second one includes the papers discussing about the impacts of maintenance activities on the three pillars of sustainability, i.e. economy, environment, and society. The third cluster isolates the papers that proposed methodologies, policies, models and tools for maintenance management in a sustainable perspective. The fourth research cluster identifies the papers that were mainly focused on the measures for sustainable maintenance performance, whereas the last research cluster includes the very recent papers discussing about the big potentiality of the enabling technologies 4.0 for supporting maintenance management in a sustainable way.

Hence, through the reading of the papers, it was possible to classify all the documents according to one or more than one research clusters, covering all the clusters and more easily identifying research gaps and future opportunities.

Each cluster is discussed in detail in the following subsections.

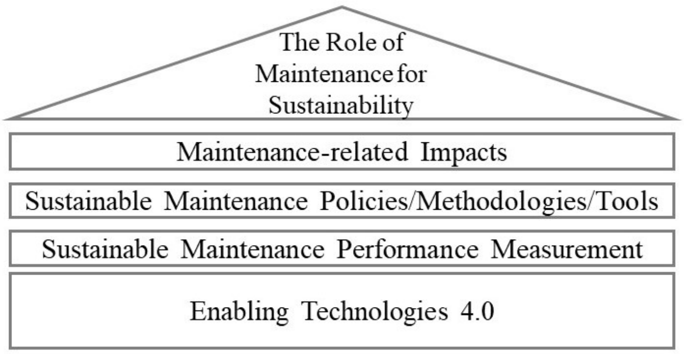

Figure I.4.1 – *Research Clusters*

I.4.1 The Role of Maintenance for Sustainability

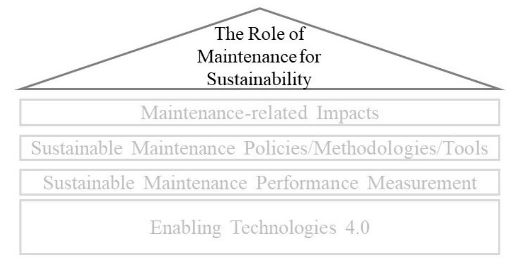

Figure I.4.2 – *Research cluster: the role of maintenance for sustainability*

The first identified research cluster (Figure I.4.2) aggregates all the selected papers that discussed in a general, qualitative, and/or descriptive way about the fundamental role of maintenance processes for contributing to the sustainability of production companies. For these reasons, the first cluster was named ‘the role of maintenance for sustainability’ and aims to provide an overview of the available literature concerning this topic.

Maintenance influences production volume and costs, asset performance, quality of the final product, but also health and safety of people, the surrounding natural environment and the social welfare (Jasiulewicz-Kaczmarek, 2013). Nevertheless, only in the last years, the role of maintenance as contributing to the sustainable operation has attracted more attention (Ferreira et al., 2009; Lee et al., 2014; Liyanage, 2007), leading to discuss in very recent papers about the paradigm of “Sustainable Maintenance”.

Maintenance has evolved over time together with manufacturing objectives from reactive function, aimed to repair and replacing equipment and devices after breakdown happened, becoming firstly a preventive approach, then a ‘lean’ process based on waste reduction or elimination (Jasiulewicz-Kaczmarek, 2013; Stuchly and Jasiulewicz-Kaczmarek, 2014). Recently it was introduced the concept of ‘green’ maintenance (Jasiulewicz-Kaczmarek and Drozyner, 2011), its needed requirements in design and operation to reduce maintenance impact on the environment (Ajukumar and Gandhi, 2013), up to now it is considered as a process that should be managed in a ‘sustainable’ perspective.

Garetti and Taisch (2012) discussed about the role of maintenance function for promoting sustainability and then the necessity to integrate sustainability-related aspects into maintenance management in order to guarantee, among all, high asset performances, equipment availability, product quality, but also limited resource and energy consumption. They highlighted that “new maintenance concepts should improve the level of sustainability in manufacturing through innovative maintenance management practices, based on the wider perspective of asset life cycle, the extensive adoption of predictive measures, and the further exploitation of potentials available from new enabling technologies”.

Lee et al. (2014) discussed about the new thinking paradigm for maintenance that should evolve from a problem-solving function (traditional vision of maintenance as reactive function) to means for problem avoidance through a proactive and innovative approach to create added value for sustainable manufacturing operations.

Jasiulewicz-Kaczmarek (2013) and Saniuk et al. (2015) discussed about this new challenge for enterprises implementing a sustainable development approach and they defined ‘sustainable maintenance’ as “proactive maintenance operations striving to provide a balance in the financial (losses, consequences, benefits), environmental and social (welfare and satisfaction of operators and maintenance staff) dimensions”.

Such vision of maintenance leads to consider this business function as an important issue to contribute for sustainability of organisations, that results in changes in approach to this enterprise function.

A sustainable maintenance management is striving for more efficient resource and energy management, reduction of maintenance “wastes”, elimination of negative environmental impact, and guarantee of employees and stakeholders safety (Demoly and Kiritsis, 2012; Jasiulewicz-Kaczmarek and Drozyner, 2011; Jasiulewicz-Kaczmarek, 2014; Sari et al., 2015). As an investment in the future, then maintenance could be able to preserve raw materials and energy, protect the environment, and increase profits in the industrial production (Saniuk et al., 2015).

Furthermore, the complexity of today manufacturing systems, and the different internal and external factors influencing them, has led an increasing number of stakeholders (internal, such as employees, production staff or logistic staff, and external, such as spare part providers or designers of machines) to be interested in maintenance results in the economic, environmental and social dimensions (Jasiulewicz-Kaczmarek, 2013).

In this context, as pointed out by Iung and Levrat (2014), maintenance function is not simply a service to repair and conserve equipment, but it has better considered as a wide process or series of activities that need to be managed in a sustainable perspective.

In this way, maintenance can contribute to the vision of those businesses aiming to guarantee a certain level of sustainability of their processes.

I.4.2 Maintenance-Related Impacts on Sustainability

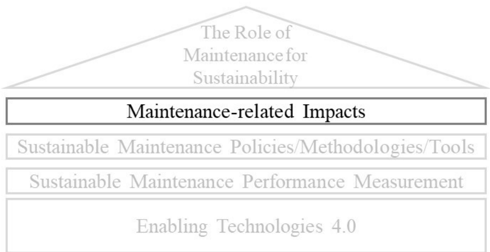

Figure I.4.3 – *Research cluster: maintenance-related impacts*

The second identified research cluster (Figure I.4.3) includes the papers that discussed about the impacts of maintenance function on the three pillars of sustainability, i.e. economy, environment, and society. Therefore, this cluster addresses the specific topic of maintenance impacts on sustainability during the execution of maintenance activities and/or as consequence of poor quality/management of maintenance performance. For these reasons, the second cluster was named ‘maintenance-related impacts on sustainability’ and aims to provide an overview of the available literature concerning this topic.

Maintenance process affects in several ways manufacturing and product performances, the surrounding environment and the society, but the maintenance impacts are often overlooked or underestimated (Fontana et al., 2015). These impacts could be on technical condition of target system (reliability and availability performance), but also on sustainability issues (safety performance, environmental damage, high consumption of energy and resources, etc.). Maintenance, in fact, affects sustainability in different way, both with direct impacts thanks/due to the execution of its processes/activities and indirect impacts on the asset to be maintained and on the manufactured product thanks/due to its efficiency/inefficiency, that turn into impacts on the mission and the vision of organisations.

Liyanage et al. (2009) proposed the basis for assessing maintenance impact on an asset’s sustainability performance during its lifecycle and for trying to assess impact in terms of gains and losses. In particular, they give rise to question: “what is the level of financial/environmental/social impact arising from excellent (poor) technical condition of system/equipment of an asset due to effective and efficient (ill-defined and/or poor) maintenance practices?” Then they provided some examples of key issues for assessment of maintenance impacts in the three sustainability dimensions and provided their insight on the issue related to maintenance work quality, highlighting that it has impact on availability and reliability (technical condition) but also consequences independent of technical aspect such as safety performance, waste produced, environmental damage, excessive resource consumption, etc. Therefore, maintenance could have a significant role in reducing economic, environmental, and social impact of industrial systems and activities (Afrinaldi et al., 2017).

From the SLR outcomes, these impacts are quite investigated.

The maintenance-related economic impacts are well-known and deeply investigated in literature. They could be direct and indirect and mainly related to costs, downtime, breakdown, wastes, low performance, waiting time, defects, extra-inventory, extra-transportation, affecting in this way the product quality and the plant productivity (Fargnoli et al., 2014; Jasiulewicz-Kaczmarek and Stachowiak, 2016; Sutrisno, Gunawan et al., 2015). In other words, inadequate plant maintenance can lead to low productivity, then lost market opportunities and lower profits, but also extra-inventory necessary to mitigate the effects of breakdowns or to repair/substitute damaged and obsolete products due to defects caused by system malfunctioning.

Maintenance-related environmental impacts are not of minor importance. However, from the SLR analysis results that only in 2009, Liyanage et al.

(2009) highlighted the necessity to consider these impacts in maintenance strategies. Ill-defined maintenance practices of manufacturing assets lead to numerous environmental problems such as hazardous emissions, production waste due to systems malfunctions, in-efficient energy usage, in-effective resource consumption, and wastage of stored materials (Kazemi, 2013; Keivanpour and Kavi, 2015; Liyanage and Badurdeen, 2010). Improper maintenance operations cause also extra-transportation that means more energy consumption and emissions together with more packaging required to protect products during movements and possible spills during transportation, or wasted energy from heating, cooling and lighting during production downtime for maintenance delay (Fargnoli et al., 2014).

Moreover, the execution of maintenance processes leads to various direct impacts of this function on the environment. However, as pointed out by Ajukumar and Ghandi (2013), maintenance role on negative environmental impact has not been adequately addressed in research and practice. For this reason, in 2013, they proposed a first classification of green maintenance requirements including environmental compatibility (e.g. leakage prevention, bio-degradable lubricants and cleaning agents, longevity materials), energy efficiency (e.g. minimizing unnecessary travel and easy to transport) and human health & safety risk (e.g. use of non-toxic lubricants and solvents). In the same year, Jasiulewicz-Kaczmarek (2013) presented the benefits from sustainable maintenance practices application and Jasiulewicz-Kaczmarek and Drozyner (2013a) discussed the role of maintenance in reducing the negative impact of a business on the environment.

Workers and stakeholders are the main actors of industry environment, and hence of the society. The main maintenance-related social impact regards human health and safety and bad maintenance practices could cause unsafe and unhealthy working conditions, accidents, and unsure incidents (Amrina and Aridharma, 2016; Jasiulewicz-Kaczmarek and Drozyner, 2013b; Khan and Haddara, 2003). Maintenance can affect not only the workers directly involved in maintenance tasks, but also all employees involved in production process or customers if poor maintenance strategies or not well-performed procedures lead to unsafe working conditions or low-quality manufactured products. Moreover, cumulative hazardous effects of pollutants due to maintenance activities cause climate change and then human health impacts (Ajukumar and Ghandi, 2013; Liyanage et al., 2009).

I.4.3 Sustainable Maintenance Policies/Methodologies/Tools

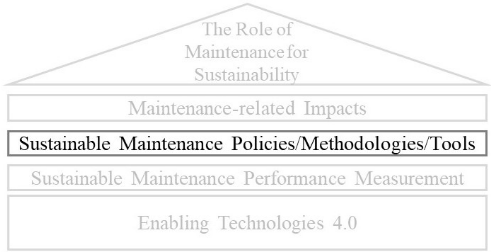

Figure I.4.4 – *Research cluster: sustainable policies/methodologies/tools*

The third identified research cluster (Figure I.4.4) involves the papers that proposed methodologies, policies, models and tools for maintenance management in a sustainable perspective and for contributing to the achievement of sustainability targets set by enterprises or imposed by external stakeholders. Therefore, the third cluster was named 'sustainable maintenance policies/methodologies/tools' and aims to provide an overview of the available literature concerning this topic.

Papers aiming to consider maintenance-related impacts on sustainability within maintenance management or striving for the proposal of new methodologies for a sustainable maintenance were found through the scoping literature review. Below, models, policies, methodologies, platforms and tools found through the SLR and developed to date, are going to be discussed. They were grouped based on their scope and objective.

Few papers were focused on the consideration and then integration of maintenance impacts on sustainability within different conventional maintenance policies and on the role that some policies have to mitigate such impacts in the transition towards sustainability.

Afrinaldi et al. (2017) developed a mathematical model optimizing the preventive replacement schedule so that the total economic and environmental impacts of an asset are minimized while Hennequin et al. (2016) proposed a joint production/periodic-preventive-maintenance strategy to minimize environmental impacts such as pollutants and greenhouse gases emissions. Cannata et al. (2009) discussed the benefits coming from e-maintenance application to limit impacts on sustainability in production process and maintenance domain.

Nezami & Yildirim (2013) and Ozcan et al. (2017) proposed methodologies based on sustainable criteria to select the most appropriate maintenance strategies or their combination among a variety of maintenance strategy alternatives, considering that the quality of maintenance work and economic, environmental and social impacts are strongly dependent on adopted maintenance policy.

Pires et al. (2015) performed a systematic literature review with the aim of finding all papers using semantic and interoperable approaches to decision making in the context of sustainable maintenance management. They concluded that such approaches were rarely seen in sustainable maintenance field and that the development of an ontology for sustainable maintenance would help maintenance systems to interoperate each other and with organisational systems to orchestrate actions, coordinate resources and interchange information, and then become more sustainable.

Some researchers were mainly focused on energy efficiency through maintenance activities striving for evaluating and reducing energy consumption as an important issue for industrial systems that aims to sustainable development. Darabnia and Demichela (2013) proposed a decision-making procedure that allows the selection of an optimum set of maintenance procedures to obtain energy savings. Instead, Hoang et al. (2015; 2016) were focused on the proposal and the integration of energy efficiency indicators within the conventional maintenance management, in particular, in condition-based maintenance decision-making. Hoang et al. (2017) proposed the novel concept of REEL (Residual Energy Efficiency Life), instead of the conventional RUL (Remaining Useful Life), to estimate the time left before the object loses its energy efficiency property. They proposed an approach for the estimation of REEL in order that a maintenance action should be done due to not only reliability, physical deterioration, age (conventional indicators), but also based on energy-efficiency (sustainable indicator). Rødseth and Schjølberg (2016) discussed the role of data-driven predictive maintenance aligned with the concept of Profit Loss Indicator (PLI) to reduce resources and energy consumption.

Other papers proposed the modification of the conventional FMEA (Failure Mode and Effect Analysis) or FMECA (Failure Mode, Effects and Criticality Analysis) methodologies for different sustainable scopes. Costantino et al. (2013) proposed the FMEECA (Failure Mode Environmental Effects and Criticality Analysis), combination of a traditional FMECA with a new parameter, the "Environmental impact", which, together with the Risk Priority Number (RPN), should influence failures' prioritization and maintenance planning. In other words, through the integration of the environmental assessment of failure modes in maintenance planning of production systems, it will be possible to prioritize failures and schedule maintenance activities considering environmental criticality of failure consequences. Sutrisno, Gunawan, et al., (2015), Sutrisno, Gunawan, and Tangkuman, (2015), and Sutrisno et al. (2016) proposed a modified FMEA to access the criticality of waste in maintenance operations, therefore to help maintenance decision maker to quantify the criticality of maintenance waste occurrence, giving the novel concept of Waste Priority

Number (WPN) to rank the risk of waste maintenance mode. They considered different categories in maintenance waste (each of them can have different waste modes and causes), such as overproduction, excessive resource utilization or excessive inventory, transportation, that affect sustainability goal. Savino et al. (2015) investigated the impact of social sustainability within maintenance operations integrating social issues, such as age and gender factors, into conventional FMEA. In particular, through a combined FMEA/AHP (Analytic Hierarchy Process), they evaluated how the criticality analysis of all the components of the plan may be affected by the impact of social aspects, in terms of age and gender of the workers.

Different tools and platforms, proposed by researchers for preventive and predictive maintenance striving for sustainability of industrial systems, were found through the SLR (Ait-Alla et al., 2017; Cannata et al., 2009; Efthymiou et al., 2012; Emec et al., 2016; Farinha et al., 2008; Farinha, 2009; Fontana et al., 2015; Mourtzis, 2016).

Some of them are briefly introduced below.

Cannata et al. (2009) discussed about the potentiality of e-maintenance platforms that can greatly enhance decision-making processes supporting the transition towards sustainable manufacturing. In fact, in maintenance domain, being the impact on sustainability often depending on timely reaction to unexpected events, an e-maintenance platform through coordination of accurate and real time information shared among different actors, emerges as a core support for sustainable manufacturing. Efthymiou et al. (2012) proposed an integrated predictive maintenance platform consisting of three pillars: data acquisition and analysis, knowledge management, and a sustainability maintenance dashboard, able to provide advisory capabilities on maintenance planning with special emphasis given to environmental and energy performance indicators, while Fontana (2015) presented a tool able to support in real time the designers so that their design decision can positively influence the economic and environmental impacts of the item maintenance phase. Later, Mourtzis et al. (2016) presented a condition-based preventive maintenance approach integrated into a machine-monitoring framework to increase sustainability of an enterprise, while Emec et al. (2016) proposed a fault-monitoring framework for manufacturing systems providing indicators for decision support in order to schedule energy-based maintenance actions and to improve resource efficiency. Ait-Alla et al. (2016) introduced the necessity to reconsider the role of maintenance for sustainable manufacturing and they presented an event driven fault detection system based on complex event processing for advanced maintenance of sustainable technical systems. The results of the proposed system indicate that it is able to detect changes in the system in real-time, reducing the time between the occurrence of emergencies and the time of their detection.

Within this research cluster, an important issue concerns the role of maintenance as enabling function for circular economy paradigm. For the first time, Takata et al. (2004) discussed the need to redefine the role of maintenance in the life cycle management and to promote the closed-loop manufacturing aiming at recovering/recycling product parts and materials.

From industrial assets point of view, the quality of asset maintenance process, to ensure sustainability compliance, requires focus on all the three main asset phases: engineering, construction and installation phase, operational phase, and decommissioning phase (Liyanage et al., 2009). Ensuring higher performance of an asset it is possible through different roles of an effective maintenance process during asset life cycle stages. This means revaluating the role of maintenance and considering it not only conventionally in operational phase, but also in design stage and decommissioning phase to analyse recoverability, reusing, or recycling of assets or parts of them.

Other researchers discussed about the potentiality of maintenance as a major lever with regards to the reuse and regeneration process support considering it as the best candidate to maintain the potential of regeneration (Diez et al., 2016; Hanatani et al., 2007; Iung and Levrat, 2014). In particular, prognostics processes do not only analyse the symptoms of faults to predict future condition and residual life, but also analyse the regeneration requirements to predict when the use of an item must be stopped to meet decomposer requirements (Diez et al., 2016). Ni et al. (2003) developed a tool to realise predictive condition-based maintenance and identification of component with significant RUL that could be efficiently and cost-effectively disassembled and reused, while Hu et al. (2015) developed an analytical decision method based on online prediction of RUL assessment for remanufacturing decisions for mechanical devices. Finally, Yan et al. (2011; 2012) proposed methodologies based on prognosis and reliability methods, to make maintenance decisions in order to evaluate and guarantee the reusability of facility for many times during its lifetime until its reuse is no longer economic.

I.4.4 Sustainable Maintenance Performance Measurement

The fourth identified research cluster (Figure I.4.5) aggregates the papers focused on the topic related to the measurement of sustainable maintenance performance and the related indicators provided by the papers. Therefore, the cluster was named ‘sustainable maintenance performance measurement’ and aims to provide the main references found through the literature review concerning this topic.

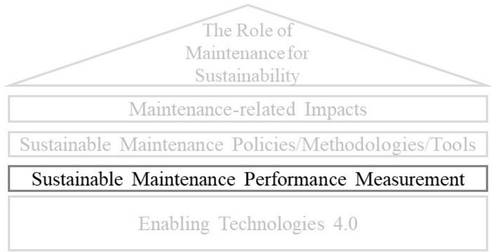

Figure I.4.5 – *Research cluster: sustainable maintenance performance measurement*

Performance measurement is a basic principle of management. Maintenance performance must be measured and monitored in order to manage and achieve the sustainable objectives of industrial companies and the necessary indicators need to be identified to meet the requirement of organisations (Parida and Galar, 2012).

As previously discussed in section I.4.2, maintenance work quality has direct and indirect impacts. Such impacts concern all the three phases of industrial asset's life, in particular the operational stage. Thus, evaluating these impacts and mitigating the sustainability risk through industrial asset maintenance, should postulate the integration of the sustainability compliance measures across phases of the asset's life (Liyanage et al., 2009).

However, Sénéchal (2016; 2017) discussed weaknesses in maintenance decision support systems for the assessment of sustainable performance, highlighting that current KPIs do not sufficiently address the social and environmental impacts of maintenance. For instance, he highlighted that EN 15341:2007 "Maintenance Key Performance Indicators" presented technical, economic, and organisational indicators, going in detail only in the economic dimension of sustainability. Furthermore, Sénéchal (2017) proposed founding elements to conduct research and development on dashboards for sustainable maintenance performance and he suggested integrating such dashboards in condition-based maintenance.

Very few studies were found through the SLR proposing sustainable maintenance performance indicators in industrial field. Sari et al. (2014; 2015), based on the review of previous studies, proposed a preliminary framework to integrate sustainability issues into maintenance performance measurement at corporate, tactical, and operational level, for automotive companies. However, they considered only some sustainability measures to assess impacts directly connected with maintenance activities, without taking into account that the inefficiency of maintenance processes causes different not-negligible indirect impacts affecting other company departments, the production process, and the final manufactured product. In fact, maintenance performance has to be measured also through its indirect impacts on sustainability aspects because, often, such impacts are not-negligible, but difficult to individuate and to estimate. Moreover, the methodology that Sari et al. (2015) used to achieve the preliminary framework consisted of a brief analysis of previous papers addressing the topic of maintenance performance measurement, which intrinsically lack an exhaustive evaluation of maintenance measures in the three sustainability dimensions. Such issue inevitably led to a not thorough framework.

Also in industrial building field, despite the idea of incorporating sustainable thinking in industrial sector has gained attention, sustainability indicators to evaluate industrial buildings' impacts on sustainability during construction, operation and maintenance, and demolition phases need to be defined (Heravi et al., 2015). Therefore, such authors proposed an investigation in this field, adopting a questionnaire survey approach to collect the experts' opinion in the petrochemical industry in Iran and, then, they presented their proposal of sustainability indicators in each building life cycle phase. Later, Amrina and Aridharma (2016) proposed a set of sixteen indicators for sustainable maintenance performance measurement, specific for cement industry, highlighting that environmental indicators are the ones has gotten high attention from companies in this field for assessing sustainable maintenance.

Other researchers tried to infer a more sustainable orientation of maintenance performance through the integration of sustainability issue in the OEE (Overall Equipment Effectiveness). Domingo and Aguado (2015) proposed the new OEEE (Overall Environmental Equipment Effectiveness) indicator to evaluate the environmental impact of asset life cycle, while Pires et al. (2016) selected and ranked some sustainability attributes from Global Reporting Initiative guidelines to correlate them to OEE dimensions and then to contribute for a sustainable maintenance performance evaluation.

I.4.5 Enabling Technologies 4.0: towards 'Maintenance 4.0' for a Sustainable Industry

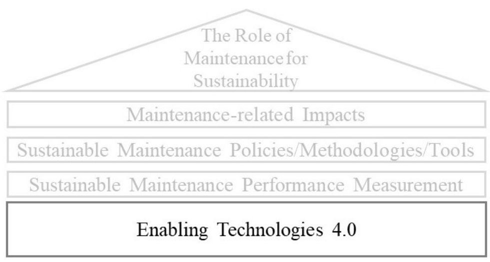

Figure I.4.6 – *Research cluster: enabling technologies 4.0*

The last identified research cluster (Figure I.4.6) involves few and very recent papers found through the SLR that discussed the big potentiality of the enabling technologies in the industry 4.0 era for contributing to the development of sustainable maintenance processes and then to a sustainable manufacturing. Accordingly, this cluster was named ‘enabling technologies 4.0: towards ‘maintenance 4.0’ for a sustainable industry’ and aims to provide an overview the available literature concerning this topic.

To achieve sustainable operation, manufacturing companies should be supported by versatile maintenance engineering infrastructure and appropriate technologies and tools. Then, the technologies of the 4th industrial revolution can become key-drivers in pursuit of sustainable maintenance and a proper asset life-cycle management.

One of the main barriers for sustainable maintenance methodologies/models/policies implementation is the lack of data, hard to collect and analyse, that could be employed to provide better support to maintenance decision-making. Emmanouilidis and Pistofidis (2011) and Jantunen et al. (2011) pointed out that the adoption of e-maintenance policy and sensor networks for condition monitoring of asset life cycle together with new signal analysis techniques and simulation models for prediction of lifetime of machinery components, can contribute to safety, quality, and sustainability of operation. In these years, smart sensor technology has been widely used by manufacturing enterprise also to monitor and track of their product in real-time (Zhang, Ren, Liu and Si, 2017). However, although many data could be collected by different systems and technologies, often no efficient methods to process and analyse data are used. In fact, the challenge is not to take as much data as possible, but to collect, store, and analyse the necessary ones to make informed decisions based upon accurate and up-to-date data (Bagle et al., 2015). Enabling technologies of industry 4.0 era can allow using the real-time and multi-source big data during the whole lifecycle to discover the hidden knowledge (Zhang Ren, Liu and Si, 2017).

In such context, different authors discussed the big potentiality (but also the complexity) of big data and analytics (Baglee et al., 2015; Campos et al., 2016; Kumar et al., 2017; Roy et al., 2016; Yao et al., 2015; Zhang, Ren, Liu and Si, 2017; Zhang, Ren, Liu, Sakao, and Huisingh, 2017) for a sustainable maintenance process. Understanding how maintenance engineering can be combined with big data potentiality is important in order to achieve the better “configuration” of big data analytics. Big data is a multi-stage process (involving data acquisition, information extraction, data modelling and analysis, and finally decision making) necessary to support the development of advanced maintenance strategies and help to solve complex technical and operational issues in maintenance (Baglee et al., 2015). The aforementioned researchers identified benefits and challenges of big data implementation, highlighting that detecting and predicting product failures, reducing operation expenses, and improving maintenance reliability are the main benefits. However, the challenges of dealing with a large amount of data, i.e. Big Data, are the diversity in data variety, uncertainties in the data, sometimes the speed of data collection and decision making for maintenance, that significantly increase the complexity of a big data-based maintenance decision support system (Roy et al., 2016). Kumar et al. (2017) highlighted the importance to consider sustainability issues in manufacturing sector and to adopt predictive maintenance to reach this goal and, accordingly, they proposed a big data analytics framework optimizing the maintenance schedule through condition-based maintenance. Instead, Zhang, Ren, Liu and Si, (2017) and Zhang, Ren, Liu, Sakao, and Huisingh (2017) highlighted the several challenges of Big Data application in product life cycle management, such as lack of reliable data and valuable knowledge employed to support the optimized decision-making of product lifecycle management; then, they proposed frameworks for Big Data driven product lifecycle management able to address these challenges.

The problem associated with this huge amount of data is the necessity for enterprises to acquire higher computing resources, processing power to analyse such data to achieve decisions and, therefore, the development and the use of cloud computing (Campos et al., 2016). Thanks to Internet of Things (IoT), different devices can be connected and the data generated from various assets can be sent to the cloud in order to be analysed and to meet maintenance objectives and strategies. IoT and cloud computing involve several advantages thanks to the wide variety of services they provide. However, use of IoT as an enabler for continuous maintenance is still at its infancy and there are still several key open issues in IoT for its adoption in the industry for the maintenance support (Roy et al., 2016). For example, providing security for the IoT enabled systems is a critical issue and data security is a crucial factor when the cloud is used. A series of properties, such as confidentiality, integrity, authentication, authorisation, availability, and privacy, must be guaranteed for IoT based future systems (Roy et al., 2016).

The enabling technology of augmented reality can be used to support maintenance workers to allow customised help and to improve safety (e.g. thanks to less human error), guaranteeing more efficiency of maintenance tasks. For example, augmented reality technology could help with legibility of text projected on surfaces, assisting the maintenance worker by providing valuable information about the maintenance task (Roy et al., 2016). Augmented reality has also significant potentiality for maintenance training tasks through the link of virtual information with physical objects, allowing training and learning of maintenance workers.

The role of ‘maintenance 4.0’ for a sustainable manufacturing is still in its infancy and it has big potentiality that need to be investigated. However, there is no contrast between old and new or conventional and sustainable, but probably a potential synergy.

I.5 Gaps and research challenges

Different gaps and research challenges (*RC*) come out from the literature analysis and from each research cluster presented in Chapter I.

The current industrial context that goes towards the fourth industrial revolution, is moving maintenance processes in "the centre of the scene", changing "the way to be seen" respect to the past. Maintenance, in fact, should contribute to guarantee the company sustainability through the right execution of its own processes and ensuring the compliance and the sustainability of the production processes and then of the manufactured products. However, a deep awareness on the role that maintenance can have to efficiently contribute to economic, environmental, and social sustainability goals of industrial companies is still missing.

Some of the analysed papers described the requirements needed to guarantee "sustainability of maintenance system", others focused on how maintenance can affect the "sustainability of target system" that have to be maintained, others focused just on one sustainability dimension. However, none considers a holistic view with a detailed classification of direct impacts of maintenance system and of non-negligible maintenance indirect impacts on sustainability of target system and target system output. In fact, while the direct economic effects of maintenance system were deeply considered in literature, the non-negligible environmental and social impacts of maintenance processes need more investigation. Moreover, although the indirect economic, environmental and social impacts of maintenance activities are not of minor importance and can strongly contribute to reduce the sustainable performance of companies, they were not deeply considered and investigated in literature. In conclusion, all studies considered only maintenance effect on sustainability in a narrow way.

Maintenance impacts on the three dimensions of sustainability should be evaluated, measured and monitored in order to be compliant with the requirements needed for sustainable maintenance, to propose improvements and reduce negative effects of maintenance performance. However, a shared general classification of indicators for measuring these direct and indirect impacts of maintenance processes on sustainability pillars, therefore the overall maintenance performance, was not found through the scoping literature review. Maintenance still uses conventional measures, mainly technical and economic, to evaluate the direct impact of maintenance performance. Although the changing role of maintenance in today's industrial environment and the necessity to know and to measure maintenance performance effects on sustainability considerations, only some authors proposed a first classification of sustainable maintenance performance measures, but they do not provide an exhaustive framework of sustainability indicators directly and indirectly affected by maintenance processes and their possible relationships.

Therefore, in order to consider maintenance and sustainability in a holistic manner, we identified three research challenges:

RC1. Identification of direct and indirect impacts of maintenance processes in the whole organisation and up to the consumer. Moreover, these impacts have to be formalised in all the three pillars of sustainability in order to be in line with existing sustainable framework and be aware of negative effects of maintenance. Therefore, definition and formalisation of the relationships between maintenance processes and sustainability indicators of different systems related to a generic organisation.

RC2. Integration of sustainability indicators in maintenance models to measure maintenance impacts and reach sustainability targets, contributing to the achievement of company sustainability goals and stakeholder's needs.

RC3. Investigation of which enabling technologies of the fourth industrial revolution can be integrated in maintenance strategies and policies, and on how integrate them, in order for supporting a sustainable maintenance management. For example, through the collection/measurement of the real-time data related to parameters to monitor and data analytics, the enabling technologies can contribute to the development of sustainable maintenance management. However, this topic is still in its infancy and needs to be investigated in depth.

The next two chapters of the thesis focuses on the first research challenge *RC1*.

In particular, *RC1* give rise to specific scientific issues, below reported:

- Identification of economic, environmental, and social impacts of maintenance processes in a generic organisation up to the customer, classifying them in 'direct impacts', achieved through the execution of maintenance activities, and 'indirect impacts' on production process and on the quality of the final product, due to maintenance efficiency/inefficiency.

- Definition of economic, environmental, and social indicators, affected by maintenance processes, that can be used to measure and control maintenance direct and indirect impacts on the three pillars of sustainability.

Therefore, in order to support the scientific issues defined in *RC1*, the next chapter provides the development of a holistic conceptual framework to help stakeholders to define maintenance direct and indirect impacts on sustainability aspects, to select the indicators of interest for measuring such impacts, and to be more aware about maintenance and sustainability relationship. Therefore, the framework is 'holistic' in two ways: from one side, because all the three dimensions of sustainability are taken into account, from another side because we consider the impacts of maintenance on different areas of the organisation, not just in maintenance system. In particular, maintenance direct and indirect impacts on sustainability were identified and then a procedure to identify and formalise sustainability indicators directly and indirectly affected by maintenance processes was defined and presented in the next chapter.

Chapter III, instead, provides a first step towards the framework validation and the spread of measurement of maintenance impacts on sustainability in industrial field.

The other identified research challenges (*RC2* and *RC3*) will be object of future research.

Chapter II

II. A conceptual framework for measuring maintenance impacts on sustainability

II.1 Introduction

Maintenance affects in several ways manufacturing and product performances, the surrounding environment and the society. In fact, maintenance processes have non-negligible impacts on sustainability performance of companies. Such impacts can be direct through the execution of maintenance activities and indirect on production process and on the quality of the final product due to maintenance efficiency/inefficiency. It is necessary to know and take into account both direct and indirect impacts of maintenance on sustainability and the systems that could be involved and affected by maintenance in order to have a holistic view on the economic, environmental and social consequences of maintenance performance and considering maintenance as a strategic lever in the organisation. Therefore, several stakeholders should consider and monitor such impacts in order to contribute to the reaching of sustainability goals fixed by company.

However, as highlighted in the chapter I.5, there are some gaps in literature. First, the direct and indirect impacts of maintenance processes on sustainability are not clearly defined in literature. Second, maintenance managers have a restrictive view considering only the direct and conventional impacts of maintenance, without taking into account that poor quality maintenance leads to non-negligible indirect impacts in other company departments/pillars. Finally, stakeholders of other company areas very often are not aware about the indirect impacts of maintenance on their own activities. Hence, it is necessary to measure such direct and indirect impacts of maintenance on sustainability in order to propose improvements and reduce negative effects of maintenance with a holistic view.

Providing a general view of all impacts of maintenance activities on sustainability aspects can help different stakeholders (e.g. maintenance managers, production managers, quality managers, plant managers, environment and safety managers) to become aware about the impacts of maintenance. In particular, from one-hand stakeholders belonging to maintenance area will become aware of the maintenance impacts on sustainability as direct output of their own activities, on another hand stakeholders belonging to other company areas will become aware of the consequences of good/bad maintenance on their own activities. Therefore, taking into account that a well-managed (poor quality) maintenance process leads to several positive (negative) consequences, and then understanding on which maintenance activities focus efforts in order to reduce such impacts.

Moreover, well-defined performance indicators can help to measure and to monitor such impacts, and to identify potential gaps between actual and desired sustainable performance of maintenance and other company departments. Such indicators can guide plant managers, production managers, maintenance managers and other stakeholders towards closing the gaps, focusing resources on specific maintenance processes and on the reduction of their impacts, in order to satisfy the fixed goals.

This chapter tries to mind these gaps and, in order to support the *RC1*, identify maintenance impacts in the organisation up to the customer on the three pillars of sustainability through the definition of the sustainability indicators of different systems directly and indirectly affected by maintenance processes. A conceptual framework for measuring maintenance impacts on sustainability including the sustainability indicators affected by maintenance processes was developed and proposed in Chapter II, as a scientific contribution to the scientific issues of the *RC1*. The proposed framework is holistic and general. It is 'holistic' in two ways: from one side, because all the three dimensions of sustainability are taken into account, from another side because we consider the impacts of maintenance on different areas of the organisation, not just in maintenance system. Moreover, the framework is 'general' because it can guide different types of stakeholders in different industrial contexts to be more aware about maintenance impacts on sustainability and to select the sustainability indicators of interest to measure and monitor.

This chapter is organised as follows. First, a general overview on maintenance processes and on the conventional measurement of maintenance performance allowed understanding the main maintenance processes and the literature available on measures used to measure maintenance impacts (Section II.2). Then, an ad-hoc methodology composed of different steps for the design of the conceptual framework was developed and provided in Section II.3. In particular, first, the purposes of the framework were defined; then, the stakeholders that can use the framework were identified. After these two steps, it was possible to define the main elements and the dimensions of the conceptual framework, and finally the content of the framework. To achieve the last aforementioned goal, an ad-hoc procedure was developed and provided in Section II.3.4 together with the achieved results. Finally, Section II.4 provides the developed conceptual framework for measuring maintenance impacts on sustainability and the explanation on how to use it with several examples.

II.2 Brief overview on conventional measurement of maintenance performance

This section provides a general overview of the conventional maintenance measures in order to provide the reader the main references on "classical" measures generally used to evaluate maintenance performance, before going towards the measuring of maintenance impacts on sustainability and the sustainable indicators monitoring.

As already reported in section I.4.4, the performance of maintenance processes has to be measured, monitored, and managed. However, differently from the purpose of this chapter II.2, section I.4.4 highlights that literature lacks of exhaustive measurement of sustainable maintenance performance and reports the few studies available on the aforementioned topic, while section I.4.2 highlights the gap of a holistic frame of maintenance related impacts on sustainability, that represent the reason of the development of the proposed framework. On this way, the purpose of this section II.2 is to provide to the reader the main references on the already available systems for maintenance performance measurement and on the conventional indicators, generally mainly technical and economic, used to measure maintenance performance.

The European Standard EN 15341:2007 defines the maintenance performance as "an outcome of complex activities which can be evaluated by appropriate indicators to measure both the actual and expected results". The standard proposed economic, technical, and organisational indicators, at three different levels, in order to help and encourage management to improve the actual maintenance performance when it is not satisfactory. The EN 17007: 2017 provided also possible initial elements that should guide in the definition of indicators related to a specific maintenance process. Such elements are directly connected with input and output defined in each process, but the direct and indirect impacts of maintenance process outputs (also function of the description of the activities of the processes) are not deeply considered in the standard. Moreover, the elements provided by the standard for the definition of the indicators are mainly technical and economic, giving the basis for the measuring of direct technical and economic performance of maintenance processes.

Different papers provided detailed reviews on maintenance performance measurement and on the main used indicators, and some of them developed frameworks to measure maintenance performance.

Parida & Chattopadhyay (2007) and Van Horenbeek & Pintelon (2014) proposed two well-structured frameworks to select the most appropriate indicators and to measure conventional maintenance performance.

Muchiri et al. (2010; 2011), Kumar et al. (2013), and Parida et al. (2015) reported the classification of maintenance indicators, commonly used in literature and in practice, dividing indicators in leading and lagging, and related respectively to the measurement of maintenance processes' performance and to maintenance results. Parida et al. (2015) provided also another classification in performance drivers, performance killers, and cost drivers factors. Muchiri et al. (2011) gave some examples about the indicators recurrent in literature with their description and unit of measurement; they mainly belong to technical and economic categories. Kumar et al. (2013) categorized the indicators, based on the available literature, in financial indicators, technical indicators, human resources-related indicators, and relating to internal processes of the department. They concluded that most of the researchers developed frameworks based on financial measures, but effective maintenance performance measurement systems should focus on total maintenance effectiveness. Simões et al. (2011) conducted a wide literature review on maintenance performance measurement, analysing more than 150 papers and concluding that the most used measures belong to technical, economic, safety and human resources categories. Moreover, they suggested future researches on performance measures aimed at capturing the human factor in maintenance performance.

Through the aforementioned papers, it was possible to extract the most used conventional indicators for the measurement of maintenance performance and impacts (Table II.2.1). However, reviews on the topic already exist; therefore, only the most recurrent measures were just reported in the Table II.2.1, without going in detail on the investigation of these measures.

Table II.2.1 – *Most used conventional maintenance performance measures*

#	**Conventional Maintenance Performance Measures**
1	Maintenance cost
2	OEE (Overall Equipment Effectiveness)
3	Availability
4	Maintenance quality
5	MTBF (Mean Time Between Failure)
6	MTTR (Mean Time To Repair)
7	Downtime
8	#Failures
9	Productivity
10	#Maintenance personnel
11	#Safety, health and environment incidents

Parida et al. (2015) raised some issues and challenges in maintenance performance measurement systems. Among them, the authors highlighted how changes in business goals, objectives, strategies, new technologies, software systems, organisational changes, can affect the success of measuring performance. Therefore, the performance measurement systems need to be proactive and dynamics and, then, the indicators associated need to change based on the company goals, the stakeholders' needs and the external regulations. Furthermore, taking into account the sustainable industrial requirements imposed by the today's environment, and considering the several impacts of maintenance on sustainability, it is compulsory first to define such impacts and then identify the indicators to monitor in order to control and reduce these impacts.

Hence, as a conclusion of the literature review on sustainable issues (section I.4.2 and section I.4.4) and maintenance performance indicators (section II.2 and section I.4.4), we only find few references and mainly based on some conventional technical indicators. Moreover, none of them addressed sustainability in a holistic manner. Instead, they focus on one of sustainability pillars. Therefore, in order to support the *RC1* defined in section I.5, the sustainability indicators affected by maintenance process performance have to be defined and formalised. Nevertheless, before going towards the measuring of maintenance impacts and the sustainable indicators monitoring, it is compulsory that company measures and uses at least the conventional maintenance impacts and indicators since they are the basic step of process monitoring.

The next section provides the methodology used for designing the conceptual framework for measuring maintenance impacts on sustainability, as a scientific contribution to the scientific issues defined in *RC1*.

II.3 Design of the conceptual framework

This section presents the steps needed to achieve the conceptual framework for supporting the scientific issues underlined in the research challenge *RC1*. A general conceptual framework is designed for providing an original scientific contribution to such *RC1* allowing defining maintenance impacts on different systems and on the three pillars of sustainability and formalising the relationships between maintenance processes and sustainability indicators of different systems related to organisations. None framework addressing these issues were found in literature.

We first give a definition of a conceptual framework. Then we present the methodology to design the conceptual framework and the main results achieved during each step.

"Conceptual frameworks are simply the current version of the researcher's map of the territory being investigated. As the explorer's knowledge on the topic improve, the map becomes correspondingly more differentiated and integrated" (Milles and Huberman, 1994).

According to Parida et al. (2015), "A conceptual framework explains, either graphically or in narrative form the main things to be studied; their key factors, constructions or variables and the presumed relationships among them". A conceptual framework can be theory driven or based on common sense, rudimentary/basic or more elaborate.

In this manuscript, we consider that a conceptual framework has to specify what will and will not be studied, to provide the dimensions and the possible relationships among the dimensions, indicated by arrows, which are based on logic (Parida et al, 2015; Rouse and Putterill, 2003).

According with the definitions of conceptual framework reported above and with the system engineering view, we defined the research questions. Considering that in Chapter I three research questions were already presented, the numbering of the research questions will start from four. The framework was designed according the following research questions that have to be answered:

RQ4 What is the purpose of the framework? For the reaching of which goals/purposes the framework can be used?
RQ5. Who is going to use the framework? Who are the stakeholders?
RQ6. What are the elements of the framework, the dimensions of the framework and the relationships among them?
RQ7. What is the content of the framework?
RQ8. How the framework can be used by the stakeholders? How the framework can guide the stakeholders based on their needs?

In particular, *RQ4* and *RQ5* allow formalising the context of the framework, giving the view of the framework as a "black box", and defining for what and from who the framework can be used. Instead, *RQ6*, *RQ7* and *RQ8*, allow going "inside the black box" and seeing of what the framework is composed and how it can be used.

The following sections are going to answer in detail each of the aforementioned research questions.

II.3.1 Definition of the purposes of the conceptual framework (RQ4)

The conceptual framework was born in order to address the first research challenge (*RC1*) defined in section I.5. Therefore, it was born for the need to know both direct and indirect effects of maintenance activities on economic, environmental and social sustainability and the different systems that could be involved and affected by maintenance processes, in order to have a holistic view and consider maintenance as a strategic lever. A framework purpose is also to provide "best practice" to support the maintenance consideration in face of sustainability issues.

The conceptual framework should be able (1) to give the stakeholders a holistic view on the maintenance impacts on sustainability and on the sustainability indicators affected by maintenance processes, and (2) to guide them in the selection of the indicators of interest based on their needs and goals. Indeed, this means that company that is going to use the framework already measures impacts of maintenance through conventional and technical indicators and it aims to be more aware about the impacts of maintenance activities on sustainability aspects.

In particular, the main purposes of the conceptual framework proposed in this thesis are two, one mainly qualitative and one quantitative:

1. To increase the awareness of different stakeholders, such as plant manager or managers of disparate business departments (e.g. maintenance managers, technical area manager, environmental pillar manager, safety manager, energy manager) about maintenance impacts on their sustainability indicators and then to guide them in the knowledge acquisition taking into account disparate indicators to monitor, which can be affected by maintenance performance. Moreover, the framework allows knowing the relationships between maintenance processes and the sustainability indicators of both maintenance system (i.e. direct impact) and of other processes of a company (i.e. indirect impact). Finally, it can guide stakeholders to ask maintenance processes sustainable requirements in order to reduce their effects on sustainability aspects.

2. To guide different stakeholders (e.g. maintenance managers, technical area managers, maintenance operators, environmental-safety pillar manager, energy manager) of production companies to build a dashboard and to measure sustainable maintenance performance and to quantify maintenance (direct and indirect) impacts on sustainability considerations, through the selection or the isolation of the sustainability indicators of interest.

Therefore, the framework allows understanding, from one hand, the maintenance processes that affect specific sustainability indicators or, from another hand, the sustainability indicators affected by a specific maintenance process. In other words, it is possible to understand the impacts of a specific maintenance process on sustainability or all the impacts on sustainability connected with maintenance.

According to the purposes of the framework, centred on sustainability, the conventional and technical indicators were not considered in this framework, because they are taken as a prerequisite for the use of the framework proposed in the thesis.

II.3.2 Definition of the stakeholders of the conceptual framework (RQ5)

The framework needs to be designed in order that different stakeholders can use its content. Moreover, if the main categories of users of the framework are known, it is possible to design the conceptual framework in a way to satisfy their needs.

Therefore, in order to design the structure of the conceptual framework, its context of usability was defined and the stakeholders that can use the framework were identified. The stakeholders who can be more interested in the framework are mainly at operational stage of asset life cycle consideration. Two main classes of internal stakeholders were identified. The first class includes the stakeholders belonging to maintenance area and interested in the measurement of maintenance performance and of maintenance direct impacts on sustainability. The second class includes the stakeholders belonging to other company areas affected by maintenance processes and interested in sustainability performance, then in indirect impacts of maintenance on their own processes. Both classes are possible "clients" of the conceptual framework provided in this chapter.

Some examples of internal stakeholders are here reported: global maintenance director, maintenance manager, technical area manager, maintenance operator, production manager, environmental pillar manager, safety manager, energy manager.

However, each stakeholder could be interested in just some aspects and some effects/consequences of maintenance activities. Therefore, the framework must be able to guide the different stakeholders in a different way, based on their needs. Some examples of stakeholders' needs are reported here. A maintenance manager can be interested in the relationships of maintenance processes and their direct impacts on sustainability considerations and, then, in defining the indicators to integrate to monitor maintenance impacts on sustainability. However, a maintenance manager can be also interested only in the impacts on one or two dimensions of sustainability. Differently, a maintenance operator of a specific process, which has a more restrictive view, can have the need to know only the impacts of his/her maintenance process on some sustainability aspects. Instead, the need of a stakeholder, which holds position in environment/safety area of a company, could be different and mainly related to the knowledge of the relationship between direct and indirect impacts of maintenance processes and environmental and social pillars of sustainability.

The content of the framework, therefore the sustainability indicators affected by maintenance processes, can be also consulted by external stakeholders, such as customers, government, investors, suppliers.

II.3.3 Definition of elements and dimensions of the conceptual framework (RQ6)

Defined the goals and the purposes of the framework, then provided the stakeholders that could be interested in a framework for the measurement of maintenance impacts on sustainability, it was possible to define the main elements and the dimensions of the conceptual framework for measuring maintenance impacts on sustainability.

The conceptual framework is composed of three dimensions and each of them involves different basic elements. The three dimensions and the elements were fixed in order to support the scientific issues defined in *RC1* (section I.5) and, then, according to the purposes of the framework and possible stakeholders needs. In particular, the *RC1* reports the necessity to identify the impacts of maintenance processes in the whole organisation and up to the customer and on all the three dimensions of sustainability. In this way, it is possible to "navigate" on the framework in order to satisfy different stakeholders' requests and needs and to identify, through their intersection, the "space of interest" of the stakeholder.

The first dimension is represented by the maintenance processes (management, realisation, and support processes – level 1 of detail, with the related sub-processes– level 2 of detail, as reported and explained in the introductive section of the thesis), defined according to the EN 17007: 2017 (Figure II.3.1). Each process can have different effects on sustainability, influencing the other maintenance processes or the other organisation processes.

The second dimension is represented by the type of maintenance impact (direct or indirect impact) and by the associated reference system (maintenance system (MS), target system (TS) to be maintained, and target system output (TSO)) (Figure II.3.2). This dimension is important because, as discussed in sub-sections II.1 and II.3.1, it is necessary to know both direct effects and indirect effects of maintenance and the different systems that could be involved and affected, with the aim of having a holistic view and considering maintenance as a strategic lever.

The third dimension is represented by the sustainability categories – economic, environmental and social (Figure II.3.3). All the three sustainability categories with the respective sub-categories have to be taken into account in order to keep a holistic perspective that is the basic of sustainability concept (Eslami et al., 2018).

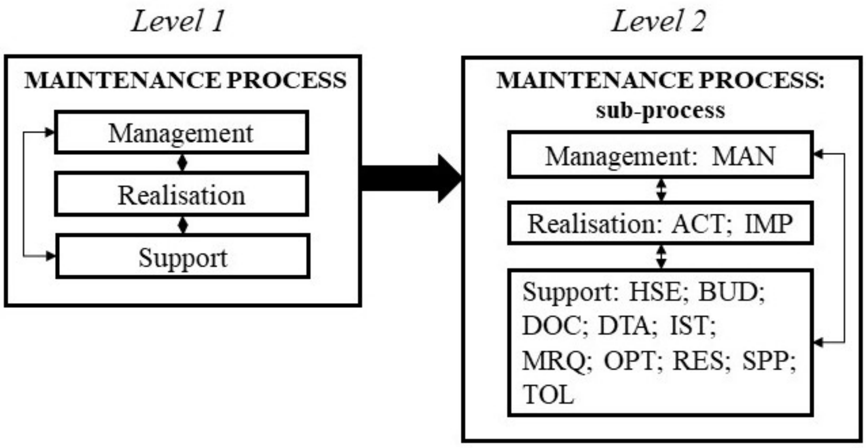

Figure II.3.1 –– *First dimension of the conceptual framework, level 1 and 2 of detail*

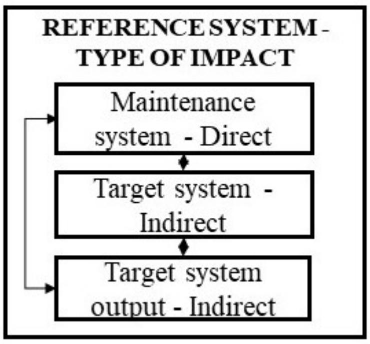

Figure II.3.2 – *Second dimension of the conceptual framework*

This third dimension can be exploded at a second level of detail. In fact, each of the three sustainability categories can be subdivided in different sub-categories. These sub-categories are going to be defined during the development of the methodological procedure reported in section II.3.4.

Each of the three dimensions are essential for the purpose of the conceptual framework and for the satisfaction of different stakeholders' needs. In particular, the intersection of the three dimensions and their elements give rise to specific "cubes of knowledge" that have to be filled with the content necessary for the measurement of direct and indirect impacts of maintenance processes on the three categories of sustainability.

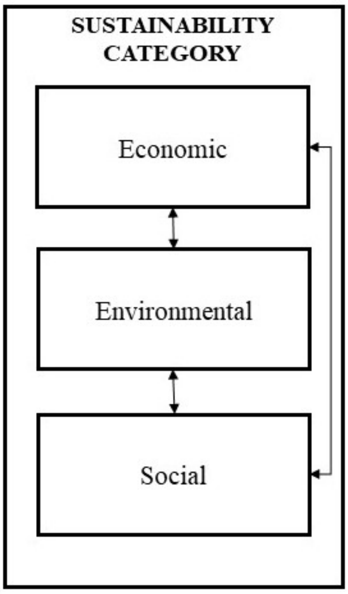

Figure II.3.3 – *Third dimension of the conceptual framework, level 1 of detail*

The next section provides the ad-hoc defined methodological procedure adopted for selecting and classifying the sustainability indicators affected by maintenance, which are going to be the content of each cube of knowledge.

II.3.4 Definition of the content of the conceptual framework: procedure for the selection of the sustainability indicators affected by maintenance (RQ7)

This section provides the methodological procedure used for addressing the *RQ7*, therefore the filling of the framework and then of the cubes of knowledge of which it is constituted. Therefore, the economic, environmental and social indicators affected by maintenance processes were identified in order to provide the content to measure maintenance impact on sustainability.

II.3.4.1 Novelty and boundaries of the procedure

This sub-section provides the novelty and the boundaries of the procedure adopted to answer the *RQ7*, then to define the content of the conceptual framework according to the scientific issues defined in the research challenge *RC1* provided in section I.5. Therefore, the framework has to include the sustainability indicators affected by maintenance processes and necessary to measure maintenance impacts on sustainability.

First, taking into account the well-known classical and technical indicators used to measure maintenance performance and available in literature (the main ones reported in chapter II.2), the methodology is going to evaluate only the sustainability indicators, namely the ones belonging to economic, environmental, and social sustainable categories. This allows providing a basis for measuring the economic, environmental and social impacts of maintenance in a holistic way. Holistic in two ways: from one side, because all the three dimensions of sustainability are taken into account, jointly from another side because we consider the impacts of maintenance on different areas of the organisation, not just in maintenance system.

The conventional and technical indicators are not included in the final version of the conceptual framework presented in the thesis. First, the classical indicators are well-known in literature and provided by some literature reviews and by the standard BS EN 15341: 2007, second, the framework was designated mainly for companies that already consider and measure conventional technical performance of maintenance and that are also interested in the evaluation of maintenance effects on sustainability pillars.

From a methodological point of view, the novelty consists of the starting point of the search. The procedure here introduced, starts from the very general sustainability indicators and, according to specific criteria, selects, classifies and adapts the ones affected by maintenance processes. In this way, it is possible to have a wide and holistic view on all sustainability aspects, avoiding losing information, and to evaluate both direct and indirect impacts of maintenance on sustainability pillars, the sustainability indicators, and the whole company performance. In particular, defining maintenance processes it is possible to know different maintenance impacts on sustainability pillars and the affected sustainability indicators that need to be monitored and used for continuous improvement. Moreover, through the proposed methodological process of selection of sustainability indicators, it is possible to provide the connection among sustainability indicators and different maintenance processes. This allows to satisfy different stakeholders' needs, according to the process(es) of interest.

The next sub-section provides the flowchart of the procedure adopted and the different steps of which it is constituted, which allow answering the *RC4*.

II.3.4.2 Flowchart of the procedure

The present sub-section explains the procedure constructed to answer the fourth research question defined and presented in section II.3.

Figure II.3.4 reports the flowchart of the procedure. In particular, the methodology is divided in three main steps, through which it will be possible to answer the *RQ7*.

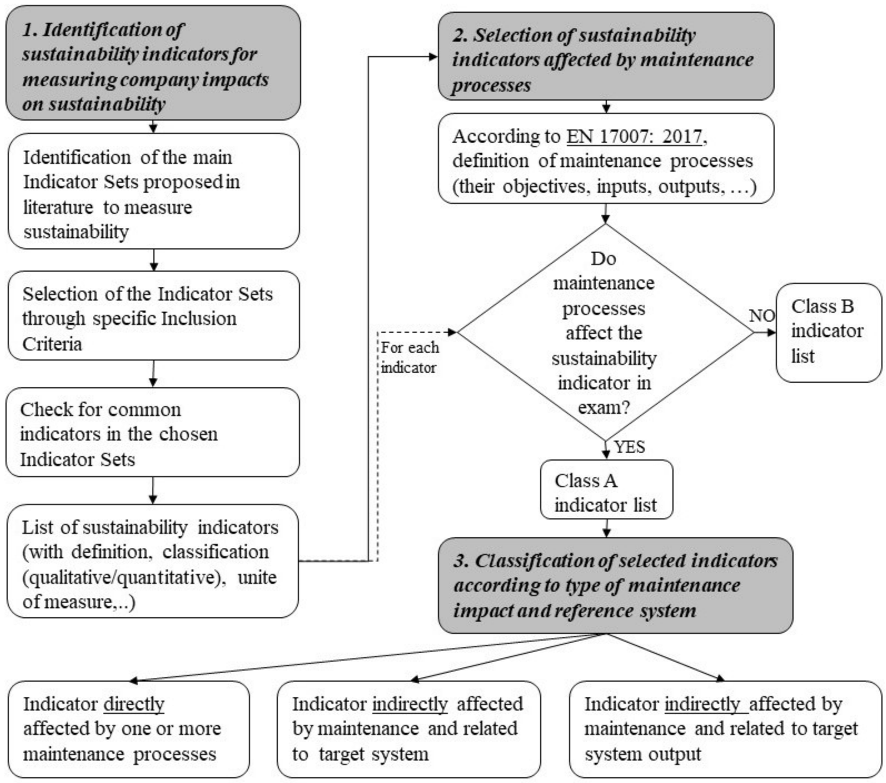

Figure II.3.4 - *Flowchart of the procedure*

The first step of the procedure aims to identify the sustainability indicators for measuring company impacts on sustainability. Then, the sustainability indicators affected by maintenance processes are selected in the second step of the procedure. Finally, the selected indicators are classified in the third step of the procedure according to type of maintenance impact and reference system. Each step is going to be explained in detail below.

The proposed procedure allows evaluating new sustainability indicators coming from other indicator sets, and deciding, following the different steps based on an objective basis, to select them or not. Following the procedure steps, it will be possible to understand if new sustainability indicators have to be added to the content of the framework.

II.3.4.2.1 Identification of sustainability indicators for measuring company impacts on sustainability

Figure II.3.5 presents the first step of the procedure, through which the sustainability indicators for measuring company impact on sustainability are identified.

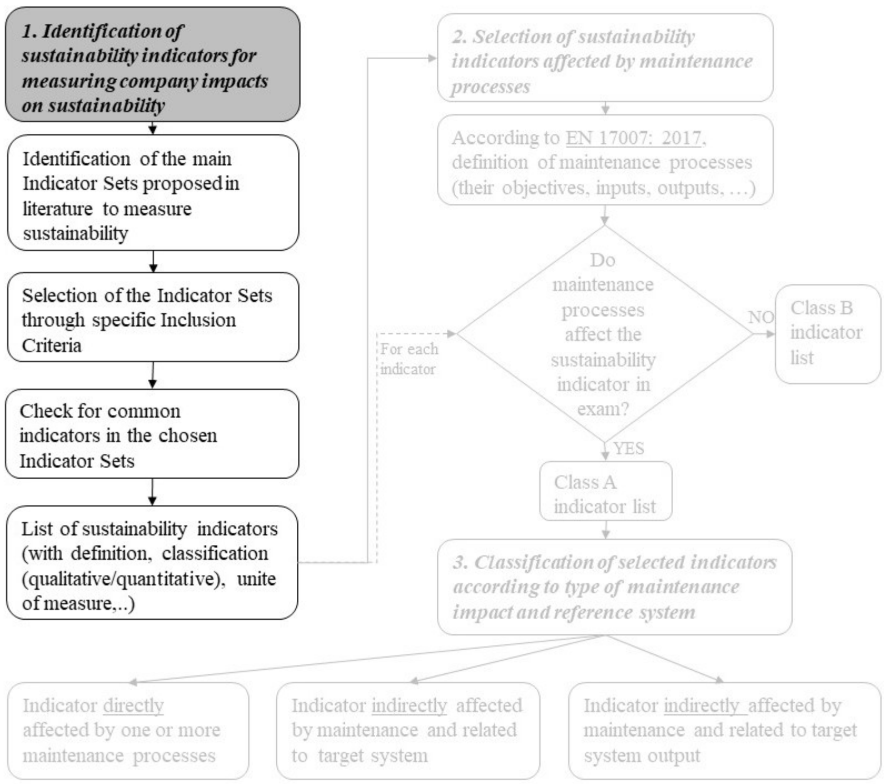

Figure II.3.5 – *First step of the procedure*

First, to start the search, general sustainable indicator sets were identified according to some specific requirements and then selected based on specific inclusion criteria.

Only indicator sets developed by specialized research centres for sustainability, or organisations for standards, or companies, were taken into account, whereas the indicator sets developed by singular researchers were not considered in the analysis because they can be too much subjective and specific to one aim. This allowed having a simplified, but exhaustive, sample of indicator sets, to be analysed for the purpose. However, if new indicator sets would be taken into account and integrated afterward, they can be analysed following the methodology steps.

According to the *RC1*, general indicators of an organisation (not specific of a domain/sector) in all the three dimensions of sustainability that can be affected by maintenance processes, have to be defined and formalised. Therefore, only indicator sets to measure impacts of a general organisation on all the three dimensions of sustainability were taken into account to be analysed. This implies that indicator sets developed to measure sustainability at national level (not only at company level) were excluded, and the indicators sets developed for a specific industrial context were not included in the final sample. This allowed taking into account and analysing general sustainability indicators, not specific of the industrial context and, then, usable for several production contexts.

According to what has just been reported above, the inclusion criteria (*IC*) identified are threefold:

IC1. The indicator set can be used for every type of organisation.

IC2. The indicator set was designed to mainly measure sustainability at company level (then, the ones designed to measure sustainability at national level were not included).

IC3. All the three dimensions of sustainability are considered in the indicator set

Once the indicator sets were chosen according to these criteria, the presence of common indicators in the selected indicator sets was checked in order to consider the right number of indicators to analyse, avoiding duplications. In this way, a list of general sustainability indicators to further analyse was achieved.

Each indicator is detailed in terms of definition, unite of measure, classification between qualitative and quantitative indicators, description or calculation value, when available.

All of this information is reported in a specific electronic spreadsheet to simplify the analysis of the indicator sets.

II.3.4.2.2 Selection of sustainability indicators affected by maintenance processes

The objective of this section is to select the sustainability indicators affected by maintenance processes. It was necessary first to understand maintenance processes and, then, verifying if a correlation exists between each indicator identified in the previous step and the activities of maintenance processes or their impacts.

Therefore, to achieve the goal of this section, first, maintenance processes were defined according to the EN 17007: 2017, which provides the purpose of the generic maintenance processes, their main activities with their description and goals, input and output, as well as the interconnections with other maintenance processes. The introductive section of the thesis provided the knowledge of the processes presented in the standard EN 17007: 2017.

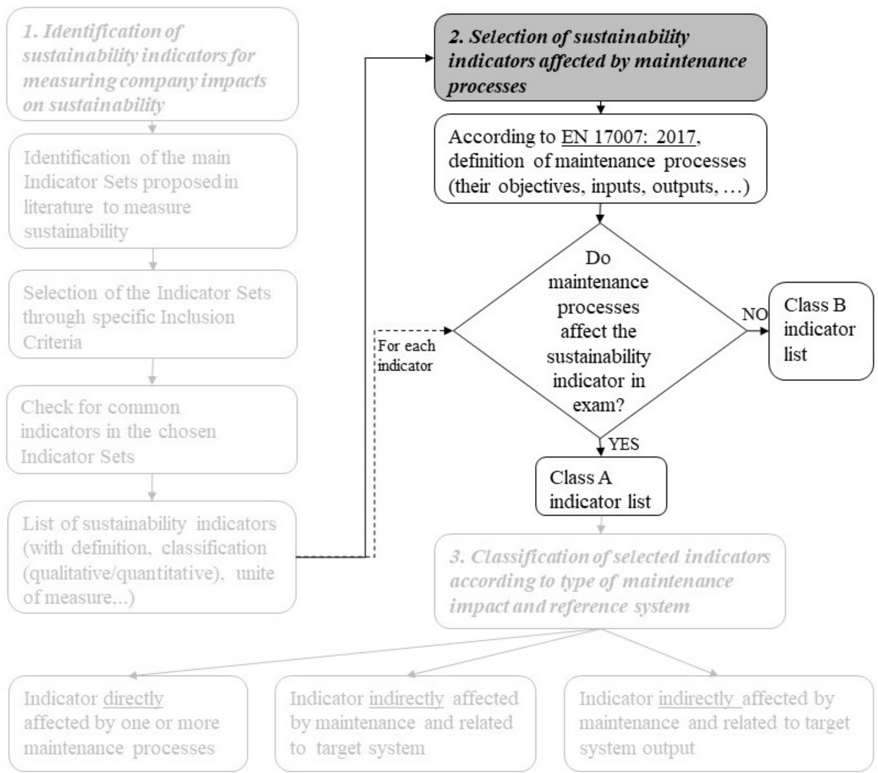

Figure II.3.6 – *Second step of the procedure*

As reported in the flowchart (Figure II.3.6), the indicators are divided in two classes: Class A or Class B, i.e. the ones affected by maintenance and the ones not affected. The indicator belonging to Class A are the ones selected to be classified and reorganised in the third step of the methodology. The Class B list involves indicators of no-interest for the proposed framework.

To define which indicators belong to Class A or to Class B, the possible connection between the maintenance processes (their sub-processes, their purposes, and their inputs/outputs) or efficiency/inefficiency of such maintenance processes and the indicators (based on their definition/ description) was established. In other words, the possible connection of the elements defined in the maintenance processes with the elements in the definition of each indicator has been considered. In particular, the maintenance processes' outputs (or their sub-processes' outputs) defined by the standard and their quality could strongly affect the sustainability indicators and the elements provided in their definition. In this last case, therefore if the connection between the maintenance processes' output (and/or the consequence of a poor quality of such outputs) and the elements of the indicators was found, then the indicator is inserted in the Class A, otherwise in Class B. In the first case, there is specific connection between maintenance activities or their efficiency/inefficiency and the indicator. In other words, the indicator is directly or indirectly affected by maintenance. In the second case, there is no specific connection and the indicator does not seem directly or indirectly affected by maintenance. However, each indicator belonging to Class B can be further explored in the future (e.g. a Delphi analysis could be conducted).

Section II.3.4.3, which presents the results of the procedure's application, provides some practical examples of indicators selected/excluded according to the criteria above described.

II.3.4.2.3 Classification of selected indicators according to type of maintenance impacts and reference system

The last step of the procedure provides for the classification of indicators selected at the previous step, according to the type of impact and the reference system (Figure II.3.7). During this classification, each indicator will be adapted with respect to the reference system. Indeed, maintenance processes can directly or indirectly affect each indicator.

In the first case, one or more maintenance processes can directly affect the considered indicator. The execution of the activities of maintenance process(es) might lead to the evolution of the indicator. In this case, the reference system is maintenance system.

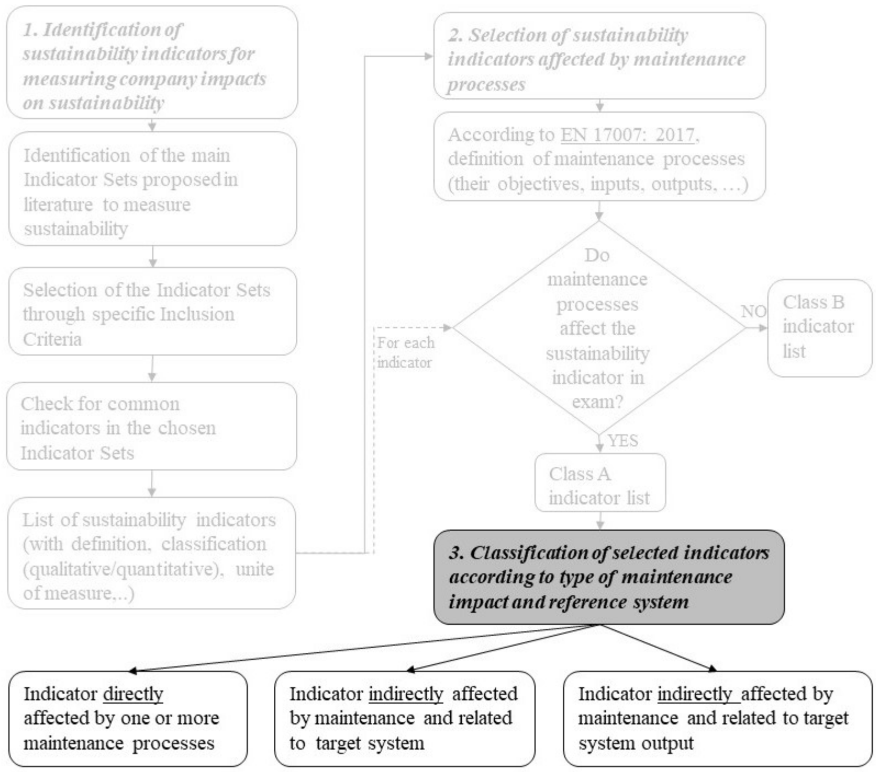

Figure II.3.7 – *Third step of the procedure*

In the second case, the indicator in exam is indirectly affected by one or more maintenance processes in a negative or positive way, respectively, as a consequence of poor-quality or inefficient maintenance, resp. well-managed, realised, and supported maintenance. In this case, the reference system is the target system that is maintained or the target system output, which correlated with the target system maintenance. If maintenance processes are not well organised, realised or supported, the target system will not work under the right condition, influencing its own performance and then its final output.

Considering that the area of interest of this thesis is mainly focused on manufacturing companies, the target system is represented by the production process, while the target system output is represented by manufactured products.

Each class A indicator can be either directly or indirectly affected by maintenance or influenced both in direct and indirect way, and then be related to more than one reference system.

II.3.4.3 Results of the procedure

Following the procedure steps, first, the main indicator sets available in literature were considered in the analysis and then selected according to the inclusion criteria defined in II.3.2. The main papers reporting literature overview on indicator sets and frameworks to assess the sustainability performance are: Chen et al. (2013), Feng and Joung, (2009), Labuschange et al. (2005), Singh et al. (2012).

Table II.3.1 provides the final list of the indicator sets taken into account in the search, their year of publication, their reference, and the three inclusion criteria.

The indicator sets respecting all the three inclusion criteria defined above, were selected.

Below, a brief description of the three selected indicator sets:

1. The "GRI (Global Reporting Initiative) standard for sustainability reporting" was developed by GRI, an independent international organisation that has pioneered sustainability reporting since 1997. The standard was designed to be used by organisations to report about their impacts on the economy, the environment, and the society. The Standard provides several disclosures in the three pillars of sustainability (see website section, ref. 1).

2. The "LCSP (Lowell Center Sustainable Production) indicator framework" was developed in 2001 by the Lowell Center for Sustainable Production of University of Massachusetts Lowell in order to promote business sustainability. The LCSP indicator framework proposed core and supplemental indicators for raising companies' awareness and measuring their progress toward sustainable production system (Veleva and Ellenbecker, 2001).

3. The "NIST (National Institute of Standards and Technology) sustainable manufacturing indicators repository" was proposed in 2011 and it provided a categorisation of sustainability indicators in five dimensions: environmental stewardship, economic growth, social well-being, technological advancement, and performance management (Joung et al., 2013). Only the first three dimensions with the associated indicators are taken into account for reaching the purpose of the framework.

Table II.3.1 – *Indicator sets taken into account to be analysed*

Indicator set	***IC1***	***IC2***	***IC3***
1. Ford Product Sustainability Index (2006) (Schmidt and Taylor, 2006)		X	X
2. GM (General Motors) Metrics for Sustainable manufacturing (2009) (see website section – ref. 2.)		X	X
3. GRI (Global Reporting Initiative) standard for sustainability reporting (2016) (see website section – ref. 1.)	X	X	X
4. IChemE (Institution of Chemical Engineers) sustainability metrics (2002) (see website section – ref. 3.)		X	X
5. LCSP (Lowell Center Sustainable Production) indicator framework (2001) (Veleva and Ellenbecker, 2001)	X	X	X
6. NIST (National Institute of Standard and Technology) sustainable manufacturing indicators repository (2011) (Joung et al., 2013)	X	X	X
7. OECD (Organization for Economic Corporation and Development) core environmental indicators (2003) (see website section – ref. 4.)			X
8. OECD (Organization for Economic Corporation and Development) toolkit (2011) (see website section – ref. 5.)	X	X	
9. EU (European Commission) sustainable development framework (2009) (see website section – ref. 6.)			X
10. UNCSD (United Nation Commission on Sustainable Development) indicators of sustainable development: guidelines and methodologies (2007) (see website section – ref. 7.)			X
11. Wuppertal Institute Sustainability Indicators (1998) (Spangenberg and Bonniot, 1998)			X

Table II.3.2 reports the total number of indicators provided by each selected set described above.

Table II.3.2 – *Indicator sets chosen and respective number of indicators*

Indicator set	#Sustainability indicators
GRI (Global Reporting Initiative) standard for sustainability reporting (2016)	77
LCSP (Lowell Center Sustainable Production) indicator framework (2001)	22
NIST (National Institute of Standard and Technology) sustainable manufacturing indicators repository (2011)	170
Total	***269***

The indicators included in these sets were analysed in detail. Among 269 indicators, first, the presence of common indicators in the three sets was checked. Therefore, the indicators belonging to the sets, but with the same definition/description and unite of measure were merged, achieving the final number of 230 indicators. Moreover, in this step, the sub-categories for each sustainability pillars were defined. They will be presented in section II.4.

Table II.3.3 presents the number of different sub-categories defined for each sustainability category and the categorization of the 230 indicators in the three pillars of sustainability.

Table II.3.3 – *Final number of indicators to analyse*

Category	#Sub-category	Final #indicators to analyse
Economic	7	36
Environmental	10	106
Social	8	88
Total	***25***	***230***

All 230 indicators are reviewed to make a final choice and to decide if they belong to Class A or Class B. In particular, following the procedure steps, among these indicators, Class A indicators were selected based on the connection between the indicator and the activities of the maintenance processes. The indicators that do not present connections are going to build the Class B.

Table II.3.4 provides the final number of the general sustainability indicators selected for Class A list, and the final number of sub-categories to which the selected indicators are associated. 124 indicators were selected, while 106 were excluded. However, Table II.3.4 presents two columns for the final number of selected indicators, respectively the third and the fourth column.

The third column includes all indicators selected and then affected by maintenance processes (124). In this list, there are two levels of aggregation of the indicators. For example, this list involves five indicators belonging to the environmental category: “reusable waste produced”, “recyclable waste produced”, “remanufacturable waste produced”, “disposable waste produced”, and “wastes generated with a breakdown by the disposal method used”. The first four indicators are included in the fifth one, which is aggregated.

The fourth column includes only the indicators belonging to the third column that are more aggregated (76). Then, while the third column includes all of the five indicators just reported in the example above, the fourth column includes only the fifth indicator, which is at low level of detail. However, when the indicators are too general and vague, such as “energy used, total, and per unit of product”, and in the final list of indicators (third column) there are also “energy consumption inside the organization”, “energy consumption outside the organization”, and “energy intensity”, which are included in the first indicator, the fourth column includes only the last three indicators, while the third column includes all of the four indicators.

To summarise, the fourth column is included in the third, while this last one involves indicators with different level of aggregation.

Table II.3.4 – *Number of indicators selected from the indicator sets*

Category	#Sub-category	#Indicators selected	#Indicators selected (low level of detail)
Economic	2	19	17
Environmental	8	72	33
Social	4	33	26
Total	***14***	***124***	***76***

When each indicator is reviewed, it is also classified, then adapted or broken down according to the type of maintenance impact (direct or indirect) and the reference system (maintenance system, target system, and target system output). This means that the final list of indicators directly and indirectly affected by maintenance is different from the number of the general sustainability indicators selected from the sets (124 or 76, based on the requested level of detail) (Table II.3.4).

Below, some examples to better explain the connection established between the activities of maintenance processes and the selected indicators, which are going to build the Class A indicator list, are reported. Such examples are indicated below with the acronym *EA* (Example of class A indicator). They are going also to show the classification of such indicators, their adaptation and breakdown.

EA1. The general sustainability indicator "Amount of waste generated by an organization, process or product specified by type and disposal method (i.e. eco-toxic, disposable, recyclable, reusable, …)" is an indicator belonging to the environmental category directly affected by all maintenance processes, because all processes produce wastes (replaced spare parts, obsolete documentations, paper, …). However, the ACT process is the most impacting process on this indicator. Figure II.3.8 shows the second level of detail of ACT process reported in the standard EN 17007: 2017. Figure II.3.8 shows in the final output, "replaced items" that are sent to a SPP sub-process to evaluate if they can be repaired or not. In the second case, they become waste and the disposal of faulty or damaged items is necessary. In this case, the indicator is adapted for the maintenance system, becoming "Amount of wastes generated by maintenance processes (e.g. replaced items, used tools, lubricants, oils, documentation) specified by waste type and disposal method (i.e. hazardous and non-hazardous, recyclable, reusable, remanufacturable, disposable)".

Moreover, the aforementioned indicator is also indirectly affected by inefficiency (efficiency) of maintenance processes. If management, realisation or support processes of maintenance function are inefficient or of poor quality (efficient or good quality), the production process could work under incorrect (correct) condition and then (do not) produce unexpected wastes or (do not) manufacture defected or non-compliant products that come back from the customer to the company. In this case, the general sustainability indicator is adapted to the reference systems respectively as "Amount of wastes generated by production process specified by waste type and disposal method (i.e. hazardous and non-hazardous, recyclable, reusable, remanufacturable, disposable)", for the target system, and "Amount of waste derived by non-compliant or defective products", for the target system output.

In such case, one general indicator is broken down in three indicators adapted to the maintenance impact and the reference system.

EA2. The general sustainability indicator "average hours of training per year = ratio between #training hours and #employees" is an indicator belonging to the social category directly affected by the maintenance process responsible of human resources (RES). Figure II.3.9 shows the second level of detail of RES process reported in the standard EN 17007: 2017. One activity of such process is "ensure training, qualification and certification of internal staff" (Figure II.3.9) that means RES affects the indicator in exam.

In this case, the indicator is adapted for the maintenance system, becoming "average hours of training per year per maintenance employees = ratio between #training hours and #maintenance employees".

The aforementioned indicator could be also related to the target system because also production employees need to be trained according to maintenance procedure. However, maintenance processes do not indirectly affect this indicator because, if maintenance is efficient or inefficient, it does not have an impact on the hours of training established for the production operators. Therefore, this indicator is not taken into account for the purpose of this research.

EA3. The general sustainability indicator “Investments and expenditures in scientific research and experimental development (R&D) for future innovative products and technologies” is an indicator belonging to the economic category mainly directly affected by the maintenance processes responsible of the budget (BUD) and of the improvement of the items (IMP). The BUD process is responsible of the economic planning for regular maintenance (expenditures and costs related to the company’s operation) and exceptional maintenance activities (investments) and then BUD process affects the indicator in exam. The purpose of the IMP process is the definition, monitoring or realisation and validation the improvements of the item, when improvement is a better solution than preventive or corrective actions to manage failures or their consequences (EN 17007:2017). Therefore, also IMP process affects the indicator in exam.

In this case, the indicator is adapted for the maintenance system, becoming “Investments and expenditures in scientific research and experimental development (R&D), e.g. for new innovative technologies, taken by maintenance processes”.

The aforementioned indicator could be related to the target system or the target system output as well because production/company manager can decide to invest for the production process or for new types of product. However, maintenance efficiency or inefficiency processes do not indirectly affect this indicator. Therefore, this indicator related to these reference systems is not taken into account for the purpose of such research.

EA4. The general sustainability indicator “Product quality assurance and management: incidents of product recalls and customer complaints, and resolutions met from these incidents” is an indicator belonging to the social category and it is indirectly affected by maintenance processes. In this case, there is no a specific connection with a process, but if management, realisation or support processes of maintenance do not operate correctly, the production process realises defected and non-compliant products that increase the number of incidents of product recalls and customer complaints.

In this case, the general indicator was classified as indirectly affected by maintenance and related to the target system output, and it does not need to be adapted.

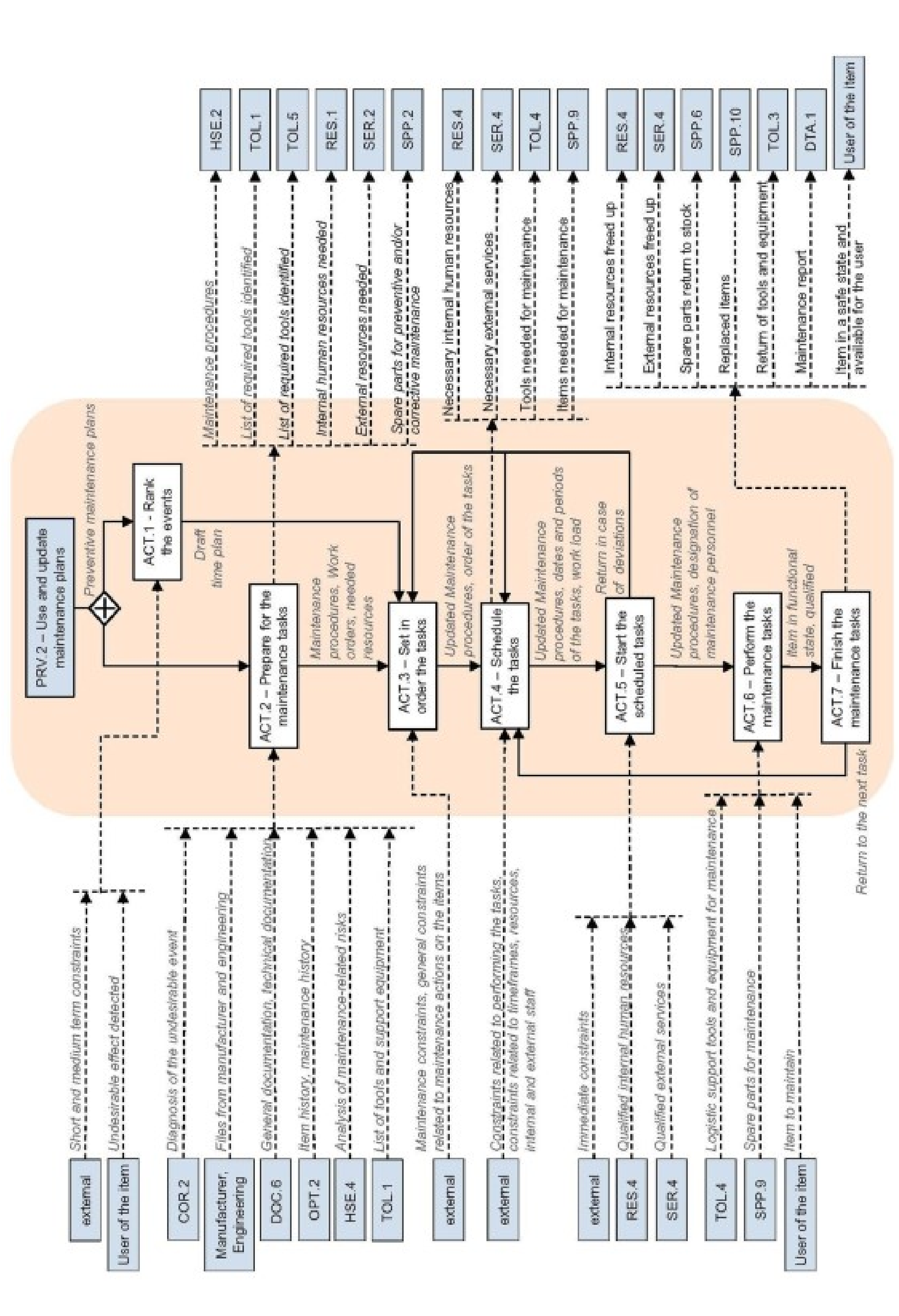

Figure II.3.8 – *Maintenance ACT process (EN 17007: 2017)*

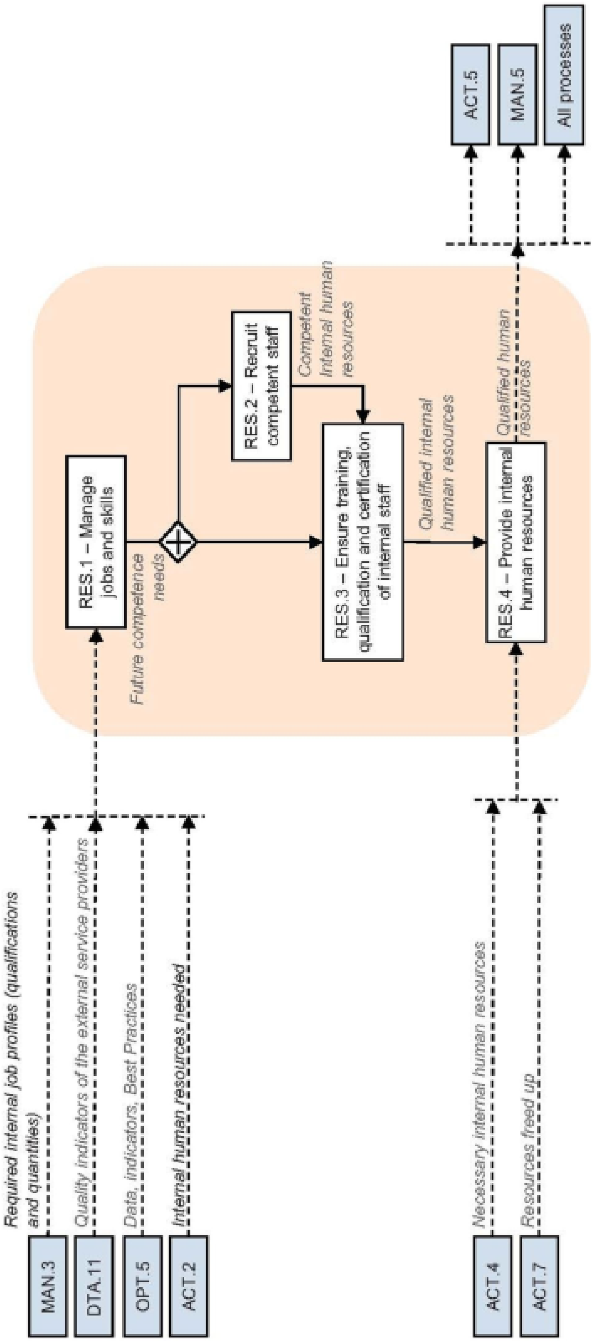

Figure II.3.9– *Maintenance RES process (EN 17007: 2017)*

Below, an example of Class B indicator (*EB*) is given.

EB1. The general sustainability indicator "total number of incidents of non-compliance with regulations and/or voluntary codes concerning marketing communications, including advertising, promotion, and sponsorship" is an indicator belonging to the social category. Based on the purposes of maintenance processes and the description of their activities reported in the standard EN 17007: 2017, the aforementioned indicator is not directly or indirectly affected by maintenance efficiency/inefficiency. Therefore, it was included in the Class B list.

All the 230 indicators (Table II.3.3) were reviewed in the way above described, in order to decide which indicators has to be selected, and then classify, adapt or break down the ones selected and affected by maintenance.

Table II.3.5 provides the number of indicators resulting from the classification/adaptation/break down of general sustainability indicators of the sets, according to the type of impact and the reference system. According to the third and the fourth columns of Table II.3.4, Table II.3.5 provides the number of indicators classified both for all selected indicators and for the ones at low level of detail.

Table II.3.5 – *Classification and breakdown of indicators based on type of maintenance impact and reference system*

#Indicators – level of detail	Maintenance system – direct impact	Target system – indirect impact	Target system output – indirect impact	#Indicators – total
Indicators classified (all)	115	74	30	219
Indicators classified (low level of detail)	68	36	20	124

From here on, for simplicity of presentation, the level of detail used in the thesis is the low level of detail. However, some aggregated indicators presented in the low level of detail can be exploded in a high level of detail, according to the stakeholders' needs.

The indicators identified in this section constitute the content of the conceptual framework (*RQ7*), which is reported in the section II.4, and each indicator will be positioned in one or more specific parts of the conceptual framework according to its dimensions presented in section II.3.3, and their intersection.

II.4 Creation of the conceptual framework for measuring maintenance impacts on sustainability

This section presents the creation of the conceptual framework designed for quantitatively measuring maintenance direct and indirect impacts on sustainability, therefore according to the purpose defined in section II.3.1. The framework is composed of the three dimensions and their elements defined in section II.3.3 and, in this section, the relationships among them were established. The interconnection of such dimensions is filled by the content of section II.3.4, therefore by the indicators defined and formalised to assess the impacts of maintenance on the three pillars of sustainability. The conceptual framework will guide stakeholders defined in section II.3.2 to satisfy their needs and requests, allowing them, from one hand, increasing their awareness on the non-negligible effects of maintenance on sustainability and, from another hand, selecting the sustainability indicators of their interest, affected by maintenance performance. Then, in section II.4.1, an explanation on how the framework can be used is reported and some examples are given.

Figure II.4.1 provides the relationships among the dimensions of the framework and the stakeholders' needs and, then, the 2D view of the conceptual framework at level 1 of detail.

The relationships among the three dimensions provide a frame in which to position the sustainability indicators identified in section II.3.4 and to isolate and focus the attention on the ones of interest according to the needs of the stakeholders but keeping a holistic perspective.

Moreover, the three dimensions of the conceptual framework and their relationships give a shared-basis to the different stakeholders (of a same company) interested in the measurement of maintenance impacts on sustainability.

In particular, the intersection between the first dimension (maintenance process) and the second dimension (reference system-type of impact) allows easily understanding the direct and indirect effects of a specific maintenance process on different reference systems.

The intersection between the first dimension (maintenance process) and the third dimension (sustainability category) allow knowing the different effects of maintenance processes on sustainability. Therefore, from one hand, what are the main processes responsible about the impacts on a specific aspect of sustainability, the indicators to consider and to monitor, from another hand what are all the impacts associated to a specific maintenance process.

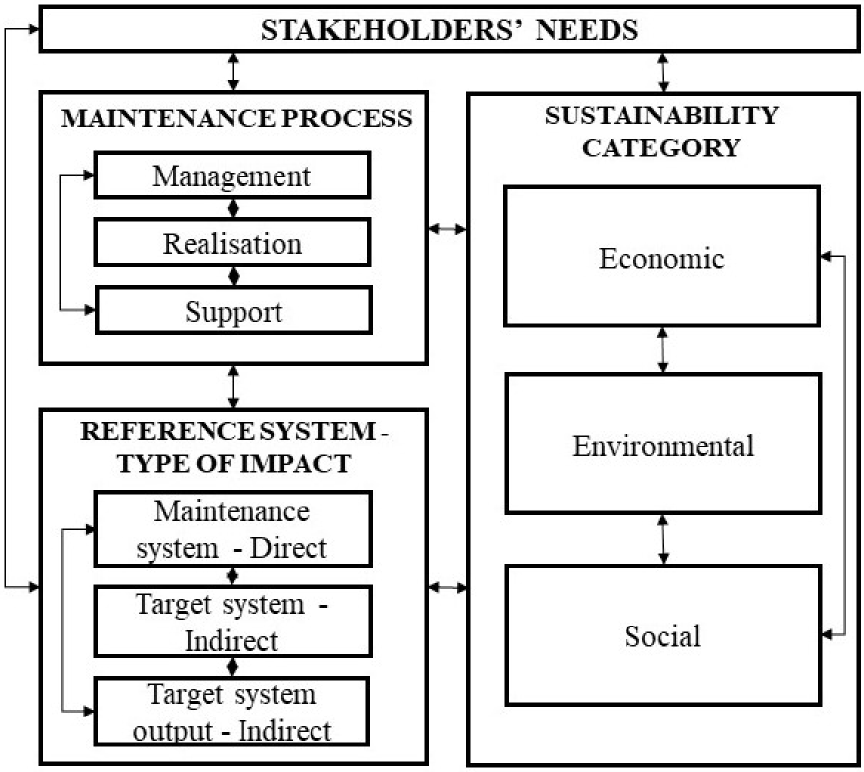

Figure II.4.1 – *Conceptual Framework for measuring maintenance impacts on sustainability - 2D view, level 1 of detail*

Finally, the intersection between the second dimension (reference system-type of impact) and the third dimension (sustainability category) gives a vision of the impact of the whole maintenance function on sustainability on different reference systems: maintenance itself, the target system (i.e. the production process) and the target system output (i.e. the manufactured product). This intersection shows direct impacts of the whole maintenance function on maintenance system and indirect impacts of maintenance on other systems in the three pillars of sustainability: economic pillar (e.g. cost of maintenance employees, cost of HSE compliance, cost of recycling), environmental pillar (e.g. losses due to energy inefficiency, waste of materials), and social pillar (e.g. employee satisfaction, customer complaints).

It is also possible to go at a second level of detail of the conceptual framework. Figure II.4.3 provides the relationships among the dimensions of the framework and the stakeholders' needs and, then, the 2D view of the conceptual framework at level two of detail of its dimensions. The second level of detail of the third dimension was defined during the procedure for selecting the indicators in section II.3.4 that allowed the definition of sustainability sub-categories.

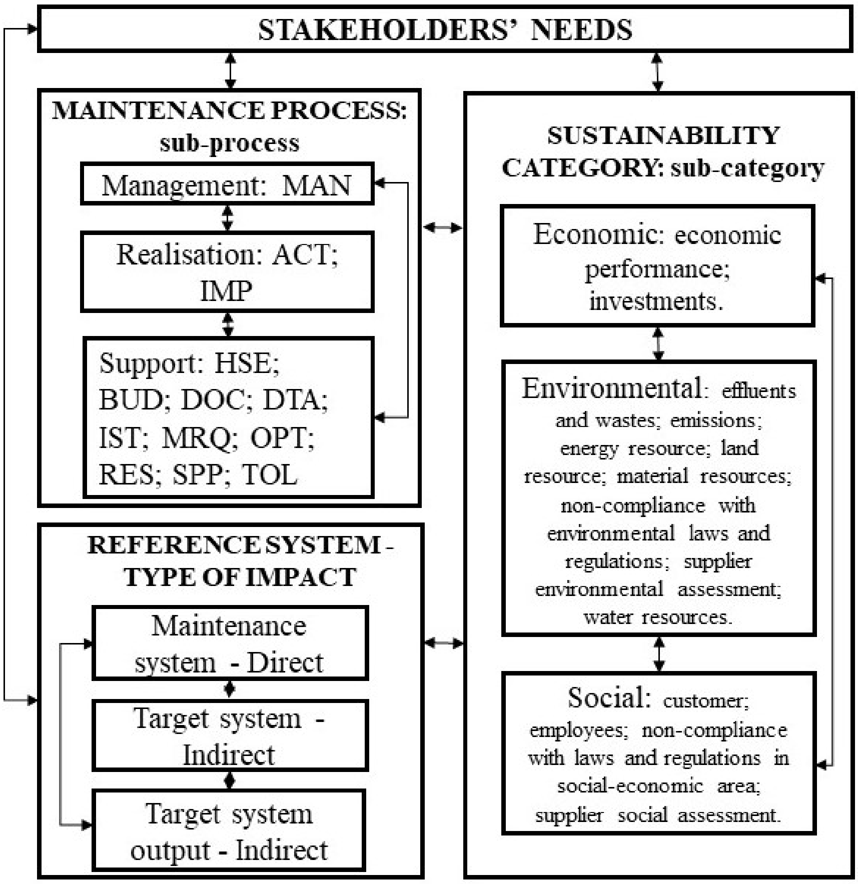

Figure II.4.2 - *Conceptual Framework for measuring maintenance impacts on sustainability - 2D view, level 2 of detail*

Figure II.4.3 provides the 3D view of the conceptual framework that better shows the interconnection between the three dimensions and the content of each intersection.

Each little cube of knowledge of the big cube constituting the conceptual framework includes several indicators.

However, going at the second level of detail of the dimensions of the framework, a more detailed representation of the 3D view of the framework was achieved (Figure II.4.4). Not all the little cubes of knowledge include indicators because some maintenance processes do not affect, directly or indirectly, specific sub-categories of sustainability. For example, the cube achieved through the intersection of TOL process, maintenance system, and "investment" sub-category of sustainability is empty because TOL process do not directly affect the investments done by the maintenance system (Figure II.4.4).

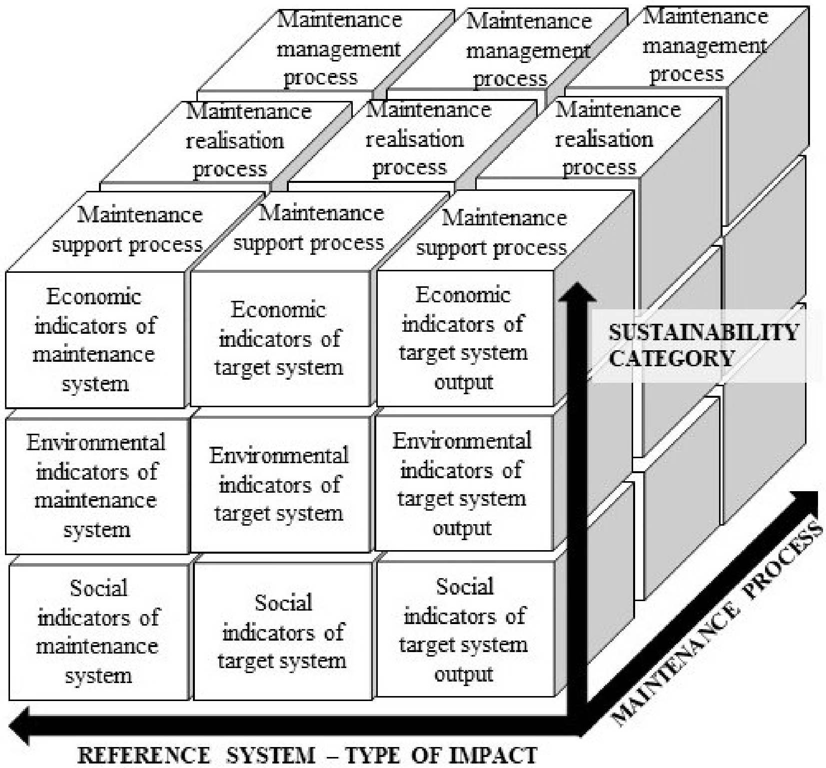

Figure II.4.3 - *Conceptual Framework for measuring maintenance impacts on sustainability - 3D view, level 1 of detail*

The first column of the framework includes the sustainability indicators directly affected by maintenance activities. In this case, the execution of each maintenance process directly affects specific indicators, and then each little cube of the first column includes different indicators (Figure II.4.4). The second and the third columns include respectively the indicators related to target system to be maintained and to the target system output and indirectly affected by maintenance. These indicators are the same for each maintenance process belonging to the first dimension of the framework. This because the efficiency or inefficiency of each process can positively or negatively affect the considered indicators but in an indirect way, then is not possible to define a-priori the execution of which maintenance process can cause an indirect impact on the sustainability indicators related to target system and its output. However, the efficient or inefficient execution of the maintenance processes affect all the indicators selected and reported in the second and third columns of the framework.

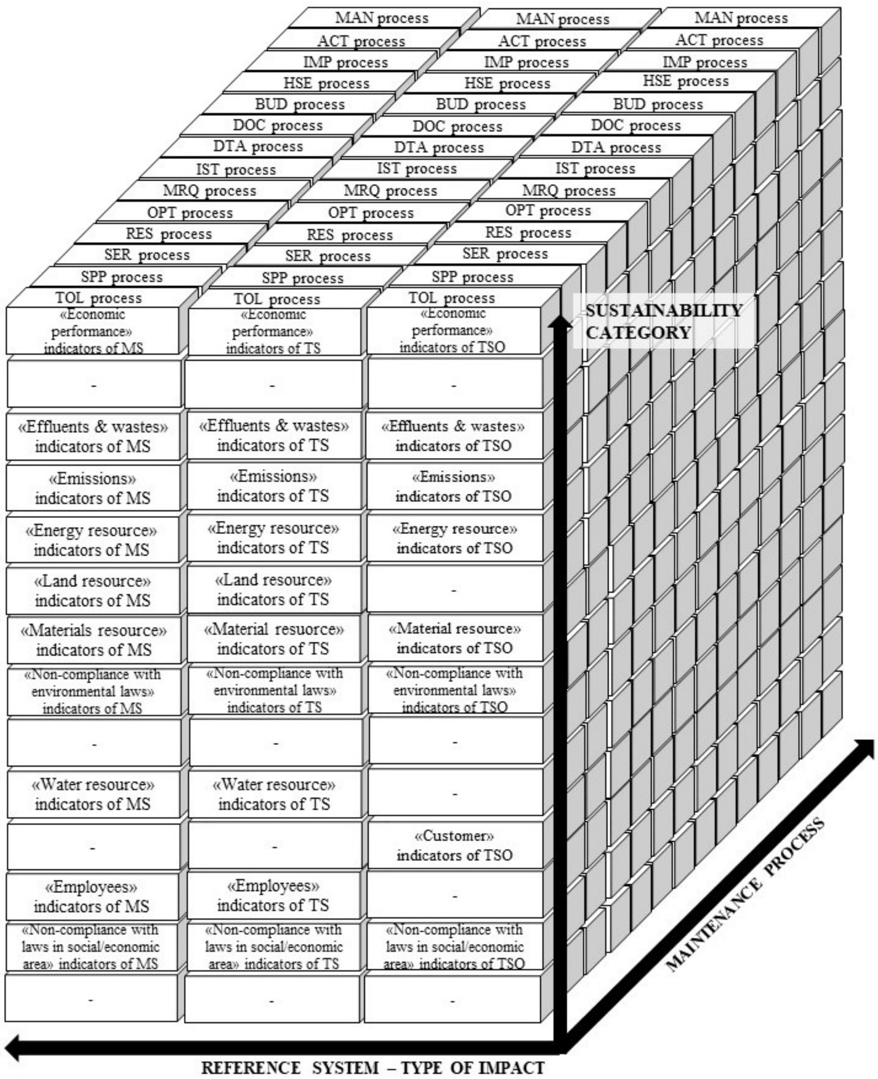

Figure II.4.4 - *Conceptual Framework for measuring maintenance impacts on sustainability - 3D view, level 2 of detail*

To clarify the content of the framework and how the selected indicators were positioned in the framework, an example is given in Figure II.4.5. The example considers all the indicators classified in the intersection of: maintenance support processes and, in particular, the "BUD" process (belonging to maintenance system – direct impact dimension); the sub-category "economic performance" (belonging to economic category of sustainability). In other words, these indicators represent the ones directly affected by the budget process of maintenance that should be taken into account for evaluating the impacts of this process on the economic pillar of sustainability.

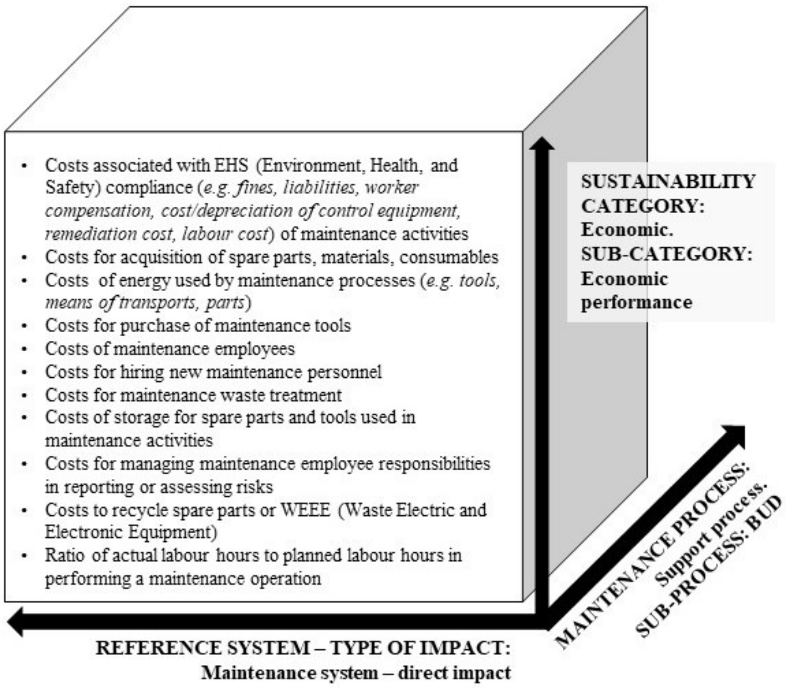

Figure II.4.5 – *Example of a little cube of the conceptual framework*

Most of the cubes of knowledge are composed of several sustainability indicators. However, for facilitating the readability of the thesis, the indicators reported in each cube of knowledge are provided in appendix in Tables A1-A51.

The next section provides the explanation on how to use the conceptual framework based on the stakeholders' requests. Some examples are given.

II.4.1 Explanation of how use the conceptual framework (RQ8)

This sub-section explains how use the conceptual framework proposed in section II.4 and then gives an answer to the *RQ8* defined in section II.3.

The developed conceptual framework is useful for different stakeholders. Each stakeholder can have different requests, as defined in section II.3.2, then different "starting points" in the framework and interests in a specific content of the framework. The framework proposes a way to navigate in it from a specific dimension to another one, based on the requests.

For example, let's consider a maintenance manager that could have different needs, then different scenarios. The framework can propose different ways of navigation on its dimensions and their relationships based on the requests of the maintenance manager.

In the first scenario, the maintenance manager is interested in knowing all direct impacts of maintenance processes. The framework has to guide him/her in the selection of all indicators involved in the intersection of maintenance system (included in the reference system-type of impact dimension), all the maintenance processes, and all sustainability categories constituted respectively the second and the third dimensions of the framework. Through these indicators, the maintenance manager can be able to measure sustainable maintenance performance in a holistic perspective and then monitor direct maintenance effects on sustainability.

Figure II.4.6 shows this first example scenario, highlighting the intersections of dimensions of interest in the framework for satisfying the request of the maintenance manager. The manager can use all the indicators involved in highlighted parts in order to reach his/her goal of measuring maintenance direct impacts on sustainability considerations. In this case, the cubes of interest are the ones under and behind the cubes highlighted in grey. These cubes are not visible from the Figure II.4.6 but all the indicators involved in the intersection of the three sustainability categories and all maintenance processes are of interest of the stakeholder and are reported in appendix in Tables A39, A40, A41, A42, A43, and A44.

In a second scenario, the maintenance manager is interested only in knowing the environmental and social impacts of the TOL process (deliver the tools, support equipment and information system). In this case, the framework can guide him/her in selecting only the indicators present in the intersection of maintenance system (included in reference system-type of impact dimension), TOL process (included in maintenance process dimension), and environmental/social categories (included in sustainability category dimension).

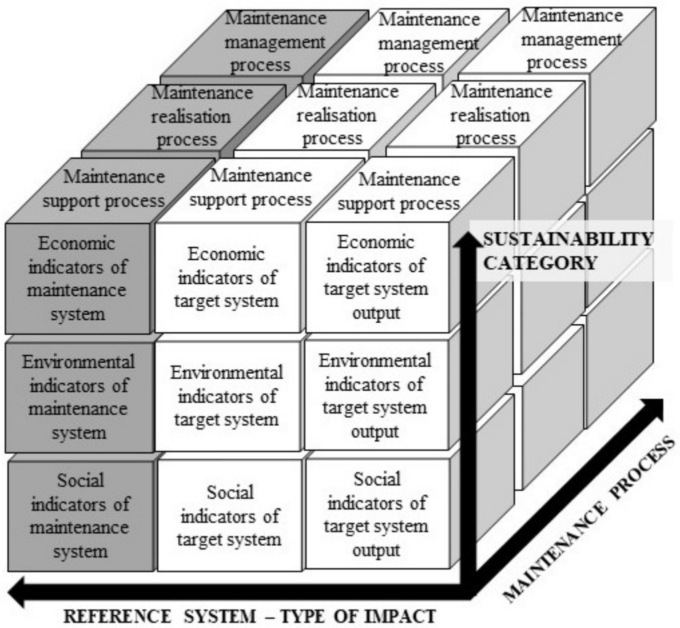

Figure II.4.6 – *Maintenance manager request: first example scenario*

Figure II.4.7 shows this second example scenario, highlighting the intersections of dimensions of interest in the framework for satisfying the request of the maintenance manager. The manager can use all the indicators involved in highlighted parts in order to reach his/her goal of measuring maintenance direct impacts on sustainability considerations. In this case, the little cubes of interest are all the ones highlighted in grey in Figure II.4.7. All the indicators involved in the intersection of environmental and social sustainability categories and TOL process are of interest of the stakeholder and are reported in appendix in Tables A36, A37, and A38.

Now, let's consider a request coming from a different stakeholder. A maintenance operator involved in the realisation process, in particular in the execution of maintenance process (ACT). He/she has a more restrictive vision, limited to the maintenance process in which he/she is involved.

In this scenario, the maintenance operator could be interested in knowing all the direct impacts of his/her specific maintenance process (i.e. action process) on sustainability. In this case, the framework will guide the stakeholder in selecting only the indicators belonging to the intersection of maintenance system (included in reference system-type of impact dimension), action process (included in the maintenance process dimension) and the three categories of sustainability (namely, all the third dimension of the framework).

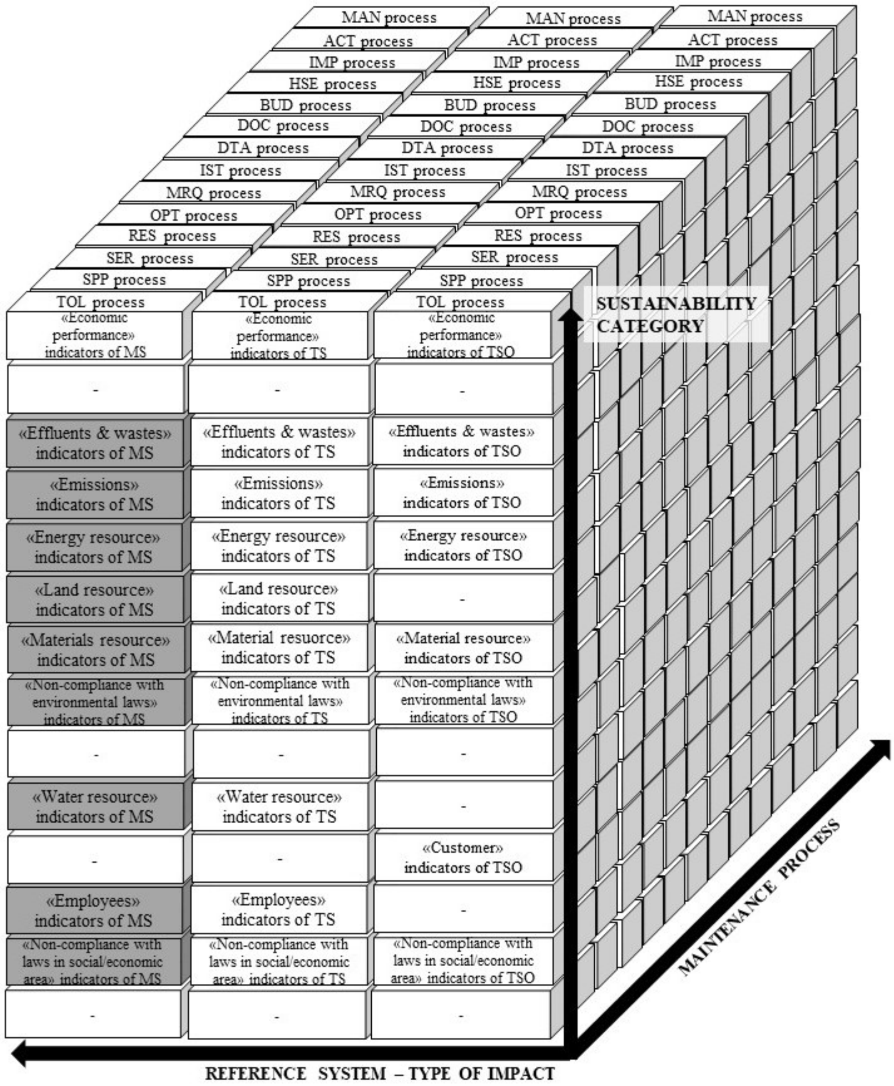

Figure II.4.7 – *Maintenance manager request: second example scenario*

Figure II.4.8 shows this third example scenario, highlighting the intersections of dimensions of interest in the framework for satisfying the request of the maintenance operator. The manager can use all the indicators involved in highlighted parts in order to reach his/her goal of measuring direct impacts on sustainability considerations of maintenance action process. In this case, the little cubes of interest are all the ones under the little cube highlighted in grey. These little cubes are not visible from the

Figure II.4.8 but all the indicators involved in these cubes are of interest of the stakeholder and reported in appendix in Tables A6, A7, and A8.

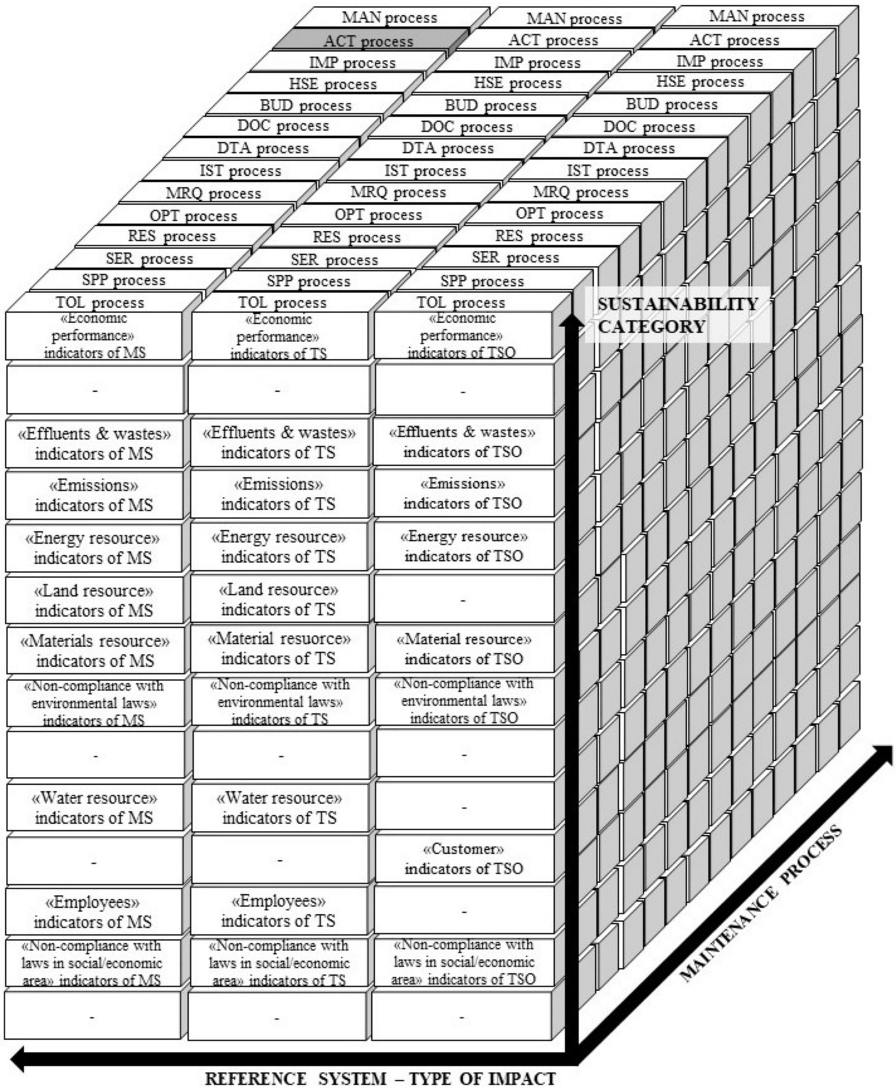

Figure II.4.8 – *Maintenance operator request: third example scenario*

Now, let's consider a request coming from an environment and safety manager. He/she has an interest in knowing all the environmental and social indicators of his/her department that are affected directly and indirectly by maintenance processes.

In this case, the framework will guide the stakeholder in selecting the indicators belonging to the intersection of maintenance system and target system (included in reference system-type of impact dimension), all maintenance processes (namely, all the second dimension of the framework), and the two environmental and social categories of sustainability (included in third dimension of the framework).

Figure II.4.9 shows this fourth example scenario, highlighting the intersections of dimensions of interest in the framework for satisfying the request of the environment and safety manager. The framework can guide the manager to know all the environmental and social indicators directly and indirectly affected by maintenance. Through this knowledge, the manager can understand the need to intervene and to take into account the effect of maintenance on the environment and social aspects of interest. He/she will be able to propose improvement on specific maintenance activities in order to reduce the impact of maintenance on his/her indicators. In this case, the little cubes of interest are all the ones behind the little cubes highlighted in grey. These little cubes are not visible from the Figure II.4.9 but all the indicators involved in the intersection of environmental and social sustainability categories and all maintenance processes are of interest of the stakeholder and are reported in appendix in Tables A40, A41, A42, A43 A44, A46, A47, and A48.

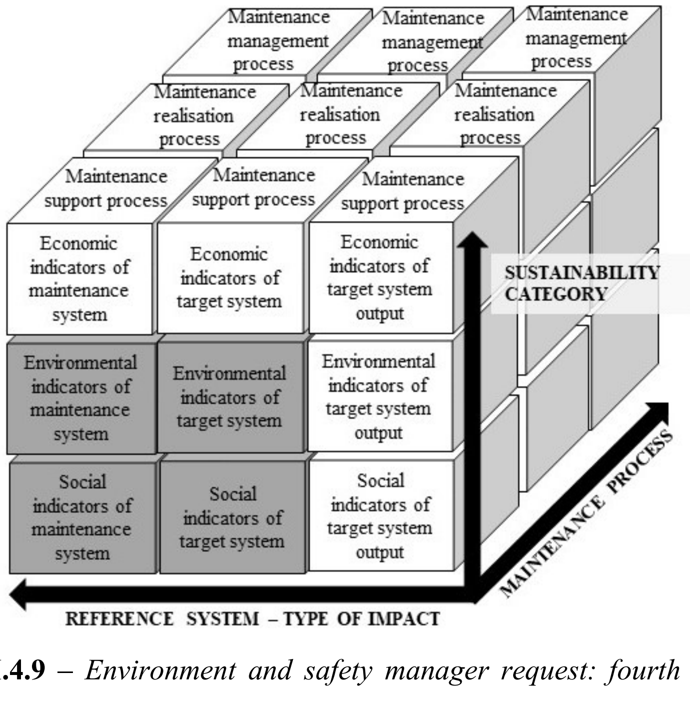

Figure II.4.9 – *Environment and safety manager request: fourth example scenario*

Now, let's consider the last case scenario. A quality manager interested in knowing all the impacts of maintenance on the quality of the manufactured product, then how maintenance can indirectly affect the realisation of non-compliant products.

In this case, the framework will guide the stakeholder in selecting the indicators belonging to the intersection of target system output (included in reference system-type of impact dimension), all maintenance processes (namely, all the second dimension of the framework) and the categories of sustainability (namely, the third dimension of the framework). These indicators are related to the manufactured product and can be indirectly affected by maintenance activities. Knowing the indicators to monitor affecting also by maintenance processes, can help the stakeholder to propose improvement of some activities in order to guarantee the quality of the product.

Figure II.4.10 shows this last example scenario, highlighting the intersections of dimensions of interest in the framework for satisfying the request of the stakeholder. The stakeholder can take into account all the involved indicators related to the product in order to reach his/her goal and knowing maintenance indirect impacts on the product. In this scenario, the indicators associated to the product in each sustainability category are the same for the different maintenance processes. In other words, all processes of maintenance can affect the sustainability indicators related to the products divided in the three sustainability categories. All the indicators of interest of the stakeholder and are reported in appendix in Tables A49, A50 and A51.

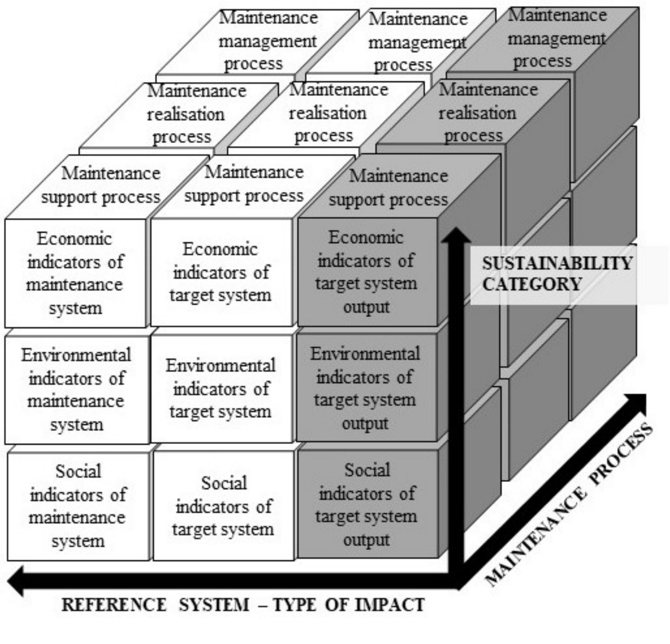

Figure II.4.10 – *Quality manager request: fifth example scenario*

II.5 Discussion

Maintenance processes have significant impacts on sustainability aspects, directly through the execution of their activities and indirectly on production process and on the quality of the manufactured product, due to maintenance efficiency/inefficiency. This should lead different stakeholders to take into account and to monitor such impacts in order to contribute to the reaching of sustainability goals of companies.

However, the impacts of maintenance processes on sustainability in the whole organisation up to the customer have not clearly been defined in literature, and the relationship between maintenance processes and sustainability indicators need to be defined and formalised.

For these reasons, a holistic conceptual framework for measuring maintenance impacts on sustainability was developed in this chapter to fill the gap. The framework is proposed as original scientific contribution to the research challenge *RC1*. The framework is holistic in two ways: from one hand, because all the three dimensions of sustainability are jointly taken into account, and, from another hand, because we consider the impacts of maintenance on different areas of the organisation and up to the customer, not just in the maintenance system.

The aim of the framework is twofold. First, providing a general view of all impacts of maintenance activities on sustainability aspects can help different stakeholders to become aware about the impacts of maintenance on different aspects. Therefore, taking into account that a well-managed (poor quality) maintenance process leads to different positive (negative) consequences. Second, well-defined performance indicators help to measure and to monitor such impacts, to identify potential gaps between actual and desired sustainable performance of maintenance and other company departments, guiding them towards closing the gaps, and focusing efforts and resources on specific maintenance processes and on the reduction of their impacts, in order to satisfy company goals.

Chapter III

III. First-step of framework validation, and spread of measurement of maintenance impacts on sustainability: a pilot survey study

III.1 Introduction

This chapter is dedicated to prove the feasibility and applicability of the conceptual framework proposed in the previous chapter and to unveil the current spread of measurement of maintenance impacts on sustainability on industrial field.

For this purpose, a pilot survey study was conducted through an ad hoc interview submitted to a sample of 18 stakeholders of several organisations in the south of Italy. The considered companies belonged to different industrial sectors in order to have a general overview and verifying the applicability of the framework as a guide for integration in any production companies of measurement of maintenance impacts on sustainability.

Therefore, through the interview, it was possible to have a first step of validation of the contents and of the way of use of the conceptual framework. It was a "first step validation" because during the interviews, the framework was not showed to the interviewed stakeholders; nevertheless, the questions were defined in order to address the content of the framework. However, a robust validation of the framework requires the discussion about the structure and the content of the framework with more stakeholders in more industrial sectors, at national and international level. This further step will be object of future research.

The interviews allowed testing the relevance of the framework, demonstrating its potential as support for several stakeholders for increasing their awareness about maintenance-sustainability relationship and for guiding them in the selection of sustainability indicators affected by maintenance processes necessary to monitor in their specific context.

Contextually, the submission of the interviews allowed also unveiling the spread of measurement of maintenance impacts on sustainability in production companies and, subsequently, understanding the main gaps.

The chapter is structured as follows.

Section III.2 provides the methodology used to reach the purpose of the pilot survey study, therefore it presents the structure of the interview submitted to the stakeholders, the characteristics of the sample, and the data collection. Section III.3 provides the detailed results of the interview, while section III.4 presents the discussion of the results and the main conclusions of the interview according to the purposes of the chapter III.

III.2 Methodology

The methodology chosen for the initial validation of the conceptual framework presented in chapter II and for unveiling the current spread of measurement of maintenance impacts on sustainability was a pilot survey study through the submission of an interview defined ad hoc for the purposes.

An empirical investigation through interviews face-to-face in multiple case study involving fifteen production companies in Italy and eighteen stakeholders was then conducted with two main purposes (1) and (2):

1. To prove the feasibility and applicability of the conceptual framework, therefore to achieve a first-step validation of the framework.

   It represents a partial validation because the framework was not showed to the companies but, through the ad hoc-defined questions submitted to disparate stakeholders, we were able to understand if the framework is able to guide different stakeholders based on their needs and the direct and indirect maintenance impacts they would measure. The objective is to validate the content of the framework and to verify if the structure of the framework is consistent in order to guide different stakeholders.
2. To unveil the spread of measurement of maintenance impacts on sustainability. Empirical evidence on current measures and indicators used to measure maintenance impacts on sustainability in production companies is then unveiled through the interview.

Therefore, this exploratory phase allows both verifying the validity of the framework and knowing the indicators used by the companies to measure and monitor maintenance impacts.

The next section III.2.1 provides the structure of the interview with its main sections defined for the aforementioned purposes, while section III.2.2 presents the sample and the collected data related to the stakeholders and their companies.

III.2.1 Structure of the interview

This sub-chapter presents the structure of the interview designed to reach the purposes defined in the previous section. In order to formulate the several questions, which are going to constitute the interview, in a correct and unambiguous way and in the right chronological order, the guidelines of Synodinos (2003) were followed. Figure III.3.1 provides the flowchart of the interview and its main elements.

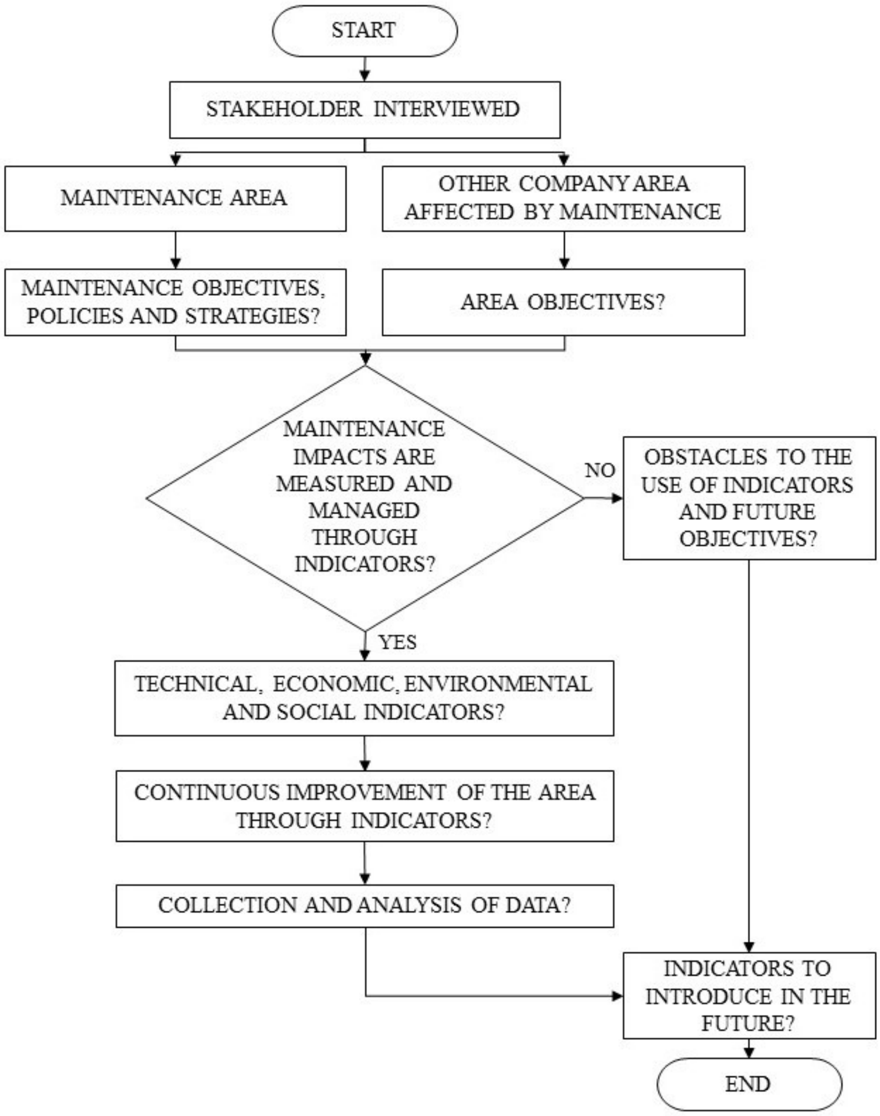

Figure III.2.1 – *Structure of the interview*

The interview was designed addressing the content and the elements of the framework and composed of different sections and questions. In particular, two main sections were identified and presented below in the following sub-sections.

III.2.1.1 Introductive section of the interview

First of all, the interview was structured in order to be submitted to stakeholders that can belong both to maintenance area or to other company areas affected by maintenance activities. In this way, it was possible to analyse the main impacts of maintenance from various perspectives. Then, the general objectives of the area, to which the interviewee belongs, were asked and, in particular, if the interviewee belong to maintenance area, the strategies and the policies adopted by maintenance function were investigated. This first section of the interview is merely introductive and allow us to get into the specific industrial context and area (Figure III.3.2).

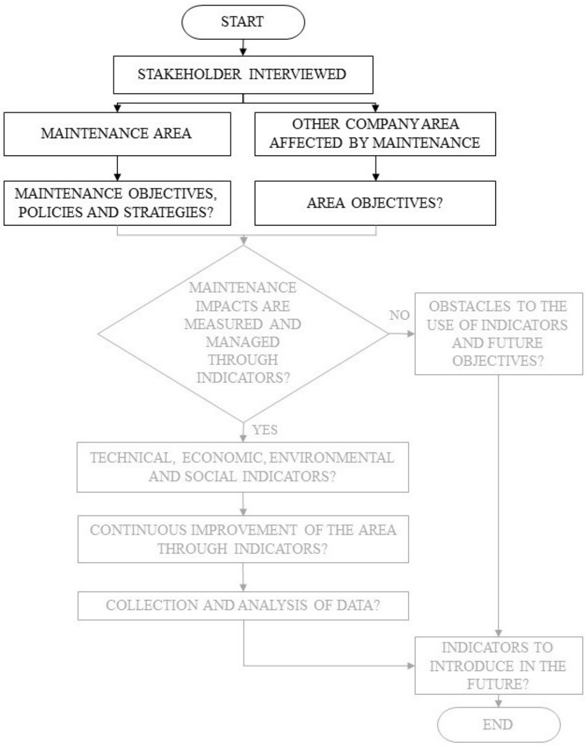

Figure III.2.2 – *Introductive section of the interview*

III.2.1.2 Core section of the interview: path 1

The core of the interview starts with a question dealing with the impacts of maintenance activities and, in particular, it was asked if they are measured or managed through specific indicators or not. Based on the answer, it is possible to continue the interview in two different paths/sections (Figure III.3.3 and Figure III.3.4).

If the stakeholder does not measure nor take into account maintenance performance and impacts, i.e. “no” output of the rhombus in the flowchart, the path of the interview highlighted in Figure III.3.3 is followed. Such path constituted the first path of the core section of the interview. In this case, the interview continued asking first, the obstacles to the use of the indicators and, then, if the area intends to introduce measures for this purpose in a near future. Therefore, before the ending of the interview, it was discussed with the interviewed stakeholder about maintenance impacts and the possibility or the convenience to introduce indicators to measure maintenance impacts.

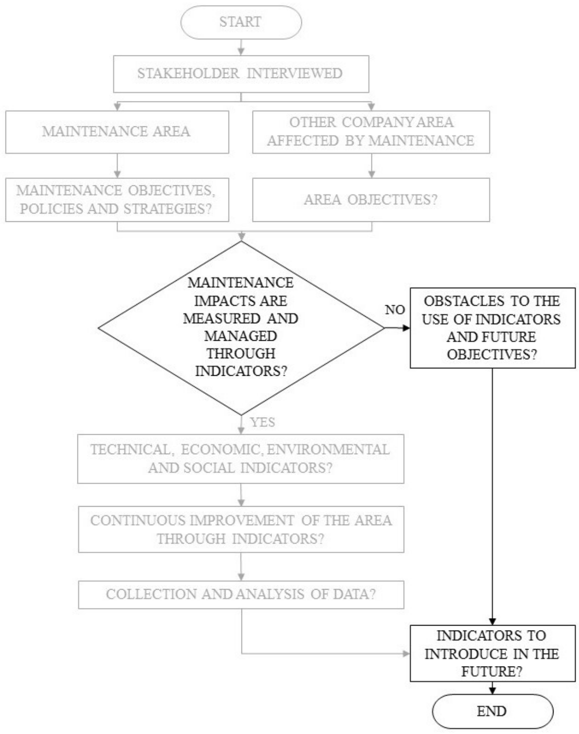

Figure III.2.3 – Core section of the interview (first path)

III.2.1.3 Core section of the interview: path 2

If the stakeholder measures maintenance performance and impacts, i.e. “yes” output of the rhombus in the flowchart, the path of the interview highlighted in Figure III.3.4 is followed. Such path constituted the second path of the core section of the interview. In this case, it was asked to the interviewee the indicators used and affected by maintenance processes, divided by category, i.e. technical indicators, economic indicators, and environmental and social ones. Then, it was asked if the aforementioned indicators are used for the continuous improvement of the company area to which the interviewee belongs and in which way. Then, other questions concerned the collection and the analysis of data needed for the calculation of the indicators and, in particular, it was asked who collects and analyses the data, how and when the collection and the analysis are performed. Finally, it was asked if the area, to which the stakeholder belongs, intends to introduce new indicators to measure maintenance impacts and it was discussed with the interviewee the possibility or the convenience to introduce new indicators for the measurement of direct or indirect maintenance impacts.

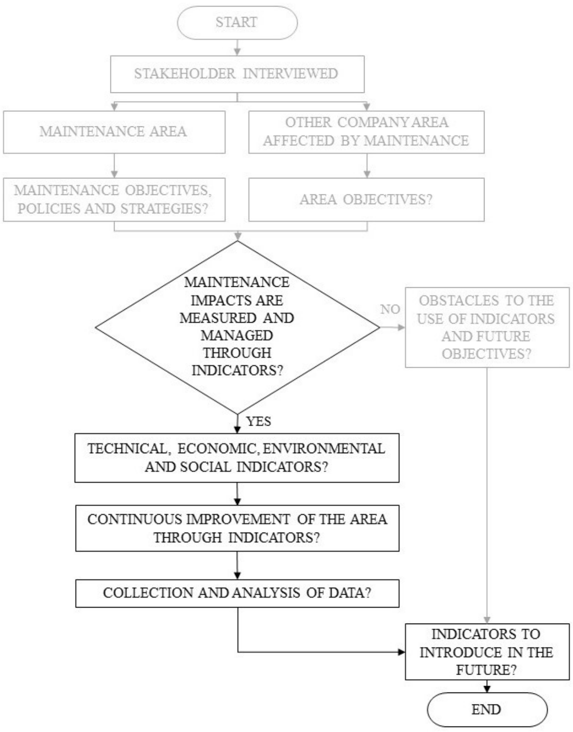

Figure III.2.4 – *Core section of the interview (second path)*

III.2.2 Sample and data collection

Stakeholders of several companies were contacted to determine their willingness to take part to the interview. By the end of this “recruiting process”, 18 stakeholders of 15 production companies accepted to be interviewed. Even if the sample does not include a large number of interviewed stakeholders, it is exhaustive and well representative of the scope we would address, i.e. explore the content of the several areas of the framework with different perspectives. In fact, different types of stakeholders, belonging to different areas of companies in several industrial sectors were interviewed (Table III.2.1). Maintenance manager, maintenance specialist, plant manager, environmental pillar manager are some example (Table III.2.1). In particular, 10 stakeholders held positions in maintenance area, 5 were plant managers, and 3 held positions in environment and safety area. In the small or medium companies, very often the figure of "maintenance manager" does not exist. When this happens, it was requested to interview the plant manager or the production manager, who were able to answer questions related to maintenance activities and their impacts. To each case (representative of the stakeholder) a letter of the alphabet was assigned and, in particular, when two stakeholders belongs to the same company a letter plus a number were assigned to them. The details of the stakeholders and the companies (to which the stakeholders belong) are reported in Table III.2.1.

The main data of the companies were collected through AIDA database, which contains comprehensive information on companies in Italy (see website section – ref.8).

The interviews were conducted across two regions of the south of Italy using the standard interview template designed for the purpose and defined in the previous section III.2.1. The interviews were conducted face-to-face or, when it was not possible, via Skype. All interviews were recorded digitally, and they lasted from half of hour to two hours, based on the availability of the stakeholders to go beyond the specific answer to the questions. In fact, the questions of the interview are very general, giving to the stakeholder the possibility to answer in a wide way, sharing relatively freely more information with the researchers, going beyond the specific answer. With some interviewees, this allowed collecting also other type of information, going beyond the goals of the company area or the specific indicators they use to measure maintenance impacts, discussing specific problems of the company related to maintenance impacts on economic, environmental, and social sustainability aspects.

Following the interviews, the recordings were transcribed, and detailed notes were drawn up. Then a detailed qualitative analysis of the answers was undertaken.

Table III.2.1 – *Involved companies and stakeholders*

CASE	INTERVIEWED STAKEHOLDER	COMPANY DIMENSION	COMPANY SECTOR	COMPANY CORE BUSINESS
A	Senior System O & M Manager	Large	Railway	Railway signalling & integrated transport systems for passenger & freight rail operations
B	Technical Area Manager	Large	Food	Production and trade of foodstuffs, in particular pasta
C	Plant Manager	Medium	Engine	Manufacture of electric motors, generators and transformers
D	Maintenance Manager	Medium	Mechanical parts and structures	Metal structural works, steel dyeing and plastic molding. The company is also engaged in the manufacturing of mechanical products, dies and abrasive products.
E1	Professional Maintenance Manager	Large	Automotive	Manufacturing, assembly and selling of motor vehicles and spare parts
E2	Environmental Pillar Manager			
F	Maintenance Specialist	Large	Automotive	Manufacturing, assembly and selling of motor vehicles and spare parts
G1	Maintenance Manager	Large	Steel	Production of laminates and electro-welded structures; metal products in iron & steel
G2	Environment & Safety Manager			
H	Plant manager	Small	Mechanical machining	Treatment & coating of metals
I	Maintenance & Safety Manager	Medium	Oil	Manufacture of machines & equipment for chemical, petrochemical & oil industries (including parts & accessories)
L	Plant manager	Small	Naval	Building of pleasure and sporting boats
M	Plant manager	Medium	Mechanical machining	Forging, pressing, stamping & roll-forming of metal; powder metallurgy
N	Plant manager	Medium	Mechanical machining	Machining
O	Maintenance & Quality Manager	Small	Plastic moulding	Plastic moulding
P	Maintenance & Part Warehouse Manager	Large	Mechanical machining	Treatment & coating of metals; machining
Q1	Maintenance Manager	Large	Automotive	Door Panels, Instrument Panels & Cockpits, Floor Consoles, Overhead Consoles, Decorative Trim & Lighting Technologies
Q2	Environment & Safety Manager			

III.3 Results

The interview results are reported below according to the structure of the interview and the three sections identified in section III.2.1.

III.3.1 Results of the introductive section of the interview

In the first introductive section of the interview, it was asked the goals of the department to which the interviewed stakeholder belongs. If the interviewee held position in the maintenance area, the maintenance strategies and the maintenance policies were asked too.

Each interviewee gave different answers on this first general question related to his/her department goals.

A keyword (or more) were associated to each given answer from the interviewees held position in maintenance, in order to classify the answers. A pie chart (Figure III.3.1) shows the classification of the answers of the different interviewees in maintenance area. Most of the answers are related to the guarantee of reliability and productivity of the operations, equipment and machines. In this case, the answers belong to reliability and productivity keywords (27%). The 13% of the stakeholders' goals are related to the respect of the right level of reliability; 20% includes also the economic goal, the 20% of the interviewees aim to guarantee the right level of quality, while the 7% aim also the right level of safety. In the 13% of the stakeholders' answers, maintenance is a business, the main goal of the company.

Instead, when we go through the answers of the interviewees belonging to environmental or safety departments, their goals were related to EHS compliance or zero impacts activities.

Below, the detailed answers of each stakeholder are reported.
In companies A and I, maintenance is a business unit that have to guarantee the operation of the system. These interviewees consider maintenance a basic function and they explained how the role of maintenance is changing during the years, becoming more and more essential for new technologies available on the market. For the interviewees D, E1, F, and L, maintenance is a function composed of different activities that need to be standardised in order to mainly guarantee the reliability of these activities and the good operation of the machines with zero failures.

According to the interviewed stakeholders G1, N, O, and P, maintenance function has to guarantee the reliability and the productivity of the plant, the proper operation of the plant, zero failures and stops, high value of the OEE.

The goals of the interviewees of companies C, H, and M, take into account both reliability and productivity, but also the safety of the people involved in the activities and the respect of the customer quality.

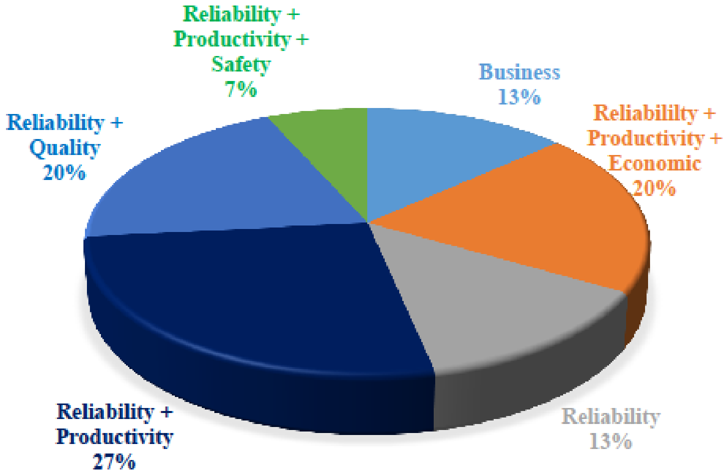

Figure III.3.1 – *Classification of goals of maintenance departments*

The interviewed stakeholders B, E1, and Q1 were respectively technical area manager, professional maintenance manager, and maintenance manager with high level of experience in the maintenance field. Therefore, they provided more detailed maintenance goals that hug reliability, productivity and economic area. The main objective of maintenance department provided by the professional maintenance manager E1 is maintaining the plant efficiency in order to produce compliance products at the minimum cost.

The main objectives of maintenance department provided by the maintenance manager Q1 and the technical area manager B are KPIs with a target to respect. These KPIs are mainly technical and economic, such as MTTR, MTBF, budget for maintenance internal and external employees, for spare parts and warehouse, for investments, and non-compliant products.

The environmental pillar manager E2 provides the goals of his department, in general and correlate with maintenance performance. The general goal of environmental pillar is zero impact and reduction of losses. However, this manager had huge experience in both maintenance and environment/energy areas and provides a detailed answer on the type of losses connected with maintenance performance. Such losses are mainly related to energy and materials consumption, and the absence of parameter optimization.

Finally, the stakeholders G2 and Q2, both environmental and safety managers, aim to EHS compliance. In particular, G2 aims to respect and maintain the safety and environmental targets imposed by external certification bodies. He highlighted that both targets are affected by maintenance. Q2, who belonged to a large and well-structured company, listed several goals of his department at corporate and operational levels, measured through several indicators that needs to stay in target. Some goals and indicators are influenced by maintenance.

To the stakeholders belonging to maintenance area, it was also asked the maintenance policies currently adopted by their companies and the ones that they would adopt for the near future. A pie chart (Figure III.3.2) shows the maintenance policies currently used by these companies. No industry uses predictive maintenance, real time or proactive maintenance, only six adopt condition based maintenance (23%), while the most frequent policies are periodic maintenance (46%) and corrective maintenance after failures (31%).

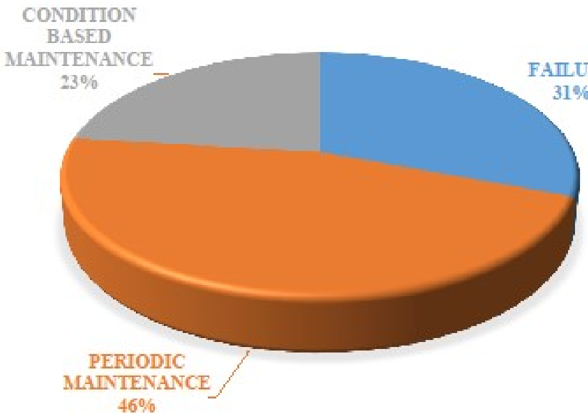

Figure III.3.2 – Maintenance policies currently used by the interviewed companies

Instead, Figure III.3.3 shows a pie chart including the maintenance policies that the interviewed companies would use in the close future. Most of the industries aim to adopt predictive maintenance (67%), or proactive (11%) or real time (11%) or periodic maintenance (11%).

Below, the detailed answers of the stakeholders.

Periodic preventive maintenance is the most used policy (according to the answers of stakeholders A, B, C, E1, F, G1, H, I, L, M, N, O, P, Q1). Planned stops for the whole plant allow executing periodic maintenance interventions through internal maintenance operators and specialists or through external maintenance. Otherwise, periodic maintenance is executed based on the operation time of the components or after a fixed number of manufactured products. Some companies act in a periodic way based on the technical component sheet or based on an internal checklist. Other companies divide components in classes of priority and, based on the impact of failure or malfunction of the component, act periodically according to the priority of each component.

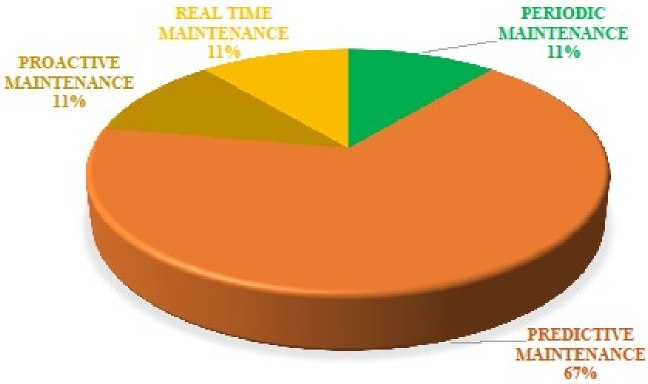

Figure III.3.3 – Maintenance policies that the interviewed companies would adopt in the future

Corrective maintenance after failures is used as well (according to the answers of stakeholders A, B, D, E1, F, G1, M, N, O). Every time a failure occurs, based on the level of difficulty of the failure, the maintenance operators or the external maintenance fixes the problem and restore the basic condition of the machine or the equipment. Stakeholder B reported that his company uses a system to tag eventual problems or failures on the production lines; professional maintenance employees read such warming or signals and they organise their activities based on the seriousness of the problem/failure and on the consequences of the stop line.

Five companies (according to stakeholders B, E1, F, G1, Q1) adopt condition based maintenance through the monitoring of vibrations, temperature or through camera for thermographic inspections. Instead, stakeholder L reported that his company uses a very simple CBM: the condition that lead the maintenance operator to do the action is just a visual control of the machine used for the production process. On the contrary, the stakeholder A reported that his company tried to use condition based maintenance but the monitoring resulted too much expensive.

Most of the stakeholders (A, C, D, I, N, P) aim to adopt predictive maintenance in the future and they are studying how integrating sensors for predicting failures or advising the maintenance operator on time. This will allow using the component as much as possible but avoiding complications connected with unexpected failures and then allows avoiding impacts on sustainability considerations. Stakeholders E1 and G1 would implement real time maintenance or proactive maintenance.

Anyway, each interviewee thinks about the future in terms of industry 4.0 or smart factory or sustainable industry, even if most of them do not have a deep knowledge and awareness on the topic. The enabling technologies 4.0 can help towards the adoption of predictive/real time/proactive maintenance policies for a smart and sustainable industry.

III.3.2 Results of the core section of the interview: path 1

Following the methodology steps, the core section of the interview was focused on the management and the measurement of maintenance impacts. In particular, it was asked if the maintenance impacts are managed or measured through indicators. Figure III.3.4 reports the answers. Four stakeholders (22%) answered the previous question negatively, while 14 stakeholders (78%) measured maintenance impacts through indicators. In this section, we focus on the four stakeholders (C, D, L, N, as reported in Figure III.3.4) that do not measure maintenance impacts, investigating the different ways of managing maintenance impacts, as well as the current obstacles and limits that prevent the use of indicators. Finally, it was asked if they intend to use indicators in the near future.

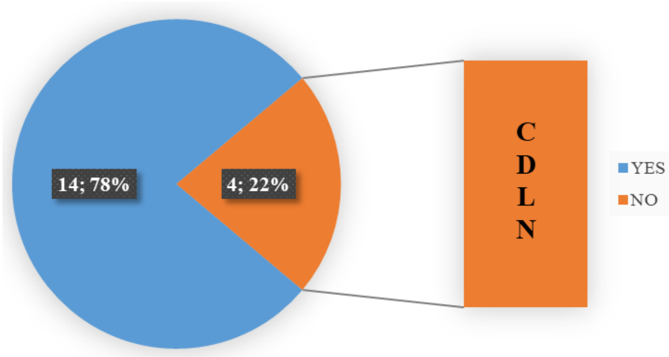

Figure III.3.4 – *Spread of measurement of maintenance impacts through indicators*

The four stakeholders that answered negatively belonged to growing company of small and medium dimensions, not still well structured.

The interviewees C and L explained that maintenance activities are managed through maintenance external contracts with periodic preventive maintenance. In particular, they explained that their company do not measure maintenance impacts because their production process (make-to-order) do not need to monitor performance of machine (as it could happen with automated machines that needs to produce large amount of pieces/day). Moreover, L explained that the main obstacles to the use of indicators is the structure of the organisation and its small dimension. Maintenance is mainly managed by failure through the prompt intervention of the parent company within the 24 hours following the failure and by periodic maintenance as reported in the maintenance booklet of the machines. For this reason, the only considered indicator is the MTBF indicated in the maintenance booklet. The monitoring of this indicator on each machine occurs by the responsible employee while the production manager coordinates all the periodic maintenance activities.

Neither C nor L intend to adopt indicators for measuring maintenance impacts in the future. Such companies see maintenance just as responsible for the availability of the machine but, considering that they adopt make-to-order production process, the machine availability is not the most important indicator to monitor. This represents the vision of small companies not aware about the impacts of maintenance on several aspects, such as the quality of the production process and then of the final product.

Differently from the previous interviewees, stakeholders D and N are interested in the measurement of maintenance impacts, but they are not still well structured. Moreover, they are trying to define the main indicators for measuring maintenance impacts and they are interested in introducing indicators and, then, in a support tool for defining the specific indicators to use in their industrial context. In particular, the interviewee D acknowledged the lack of organisation of maintenance function and he explained that his company works mainly on failures, intervening when necessary, even at very high costs. There are no accurate indicators and some data are collected but in a disorganised and careless manner. The maintenance employees write paper reports at the end of each intervention, but the data are neither transcribed in a general system nor analysed. Instead, the stakeholder N reported that maintenance is carried out by external companies and only minor maintenance interventions are entrusted to production employees. They just collect an analysis report for each intervention carried out by external companies, keeping it in the archive for possible future consultations in case of premature failures or other issues. Moreover, the data collected by the reports are analysed only superficially.

III.3.3 Results of the core section of the interview: path 2

The second path of the core section of the interview concerns the 14 stakeholders (A, B, E1, E2, F, G1, G2, H, I, M, O, P, Q1, and Q2) who use indicators to measure maintenance impacts in their industrial context.

In particular, it was asked for the used indicators, which were classified in four main categories: technical, economic, environmental, and social.

Figure III.3.5 reports the total number of indicators used by each case for measuring maintenance impacts, divided by category (technical, economic, environmental, and social).

Through a simple count, the total number of indicators collected through the interviews were 116: 35 technical indicators, 43 economic indicators, 15 environmental indicators, and 22 social indicators. However, going in detail in the type of indicators used by each case, it appears that most of the indicators are the same. Therefore, Table III.3.1 summarizes the actual number of type of indicators divided by category, with a classification of indicators directly and indirectly affected by maintenance for each category. Figure III.3.6 provides the percentage of indicators by category.

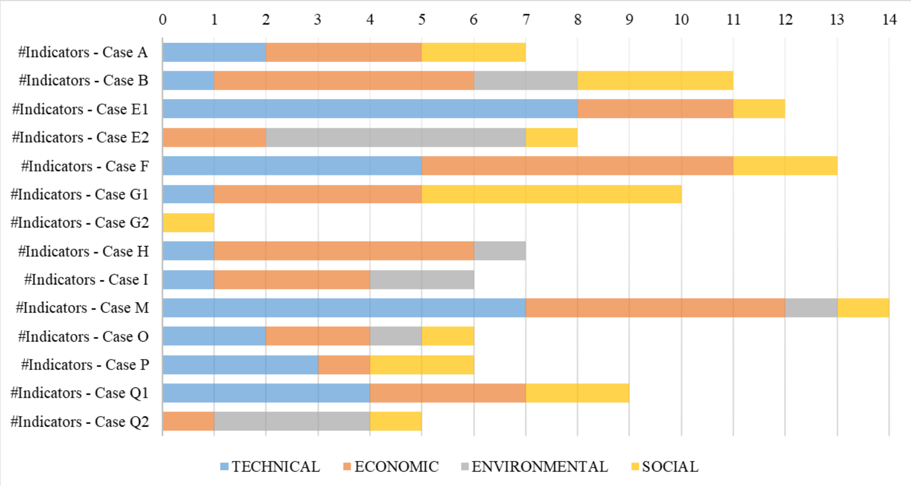

Figure III.3.5 – *Total number of indicators used by each interviewed stakeholder, divided by category*

Table III.3.1 – *Actual number of indicators divided by category*

Category	#Indicators	#Indicators (direct impact)	#Indicators (indirect impact)
Technical	16	12	4
Economic	14	10	4
Environmental	7	1	6
Social	10	7	3
Total	***47***	***30***	***17***

Going in detail of each category, the 47 indicators found through the interview are reported below in different tables, divided by category.

Table III.3.2 provides the technical indicators used by the stakeholders interviewed for the pilot survey, the associated recognition number, and the type of maintenance impact (direct/indirect) on each indicator.

Table III.3.3 reports the technical indicators defined in Table III.3.2 with their frequency of utilisation by each case. This view allows understanding the most used technical indicators.

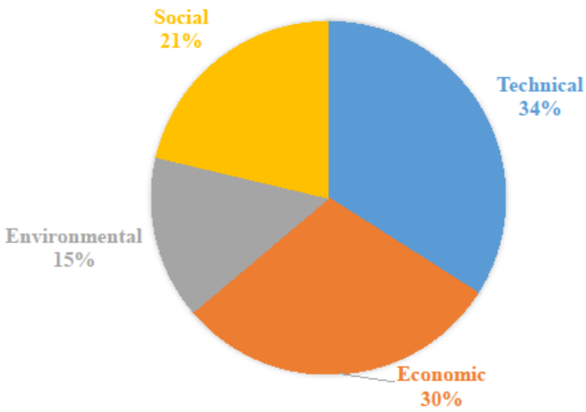

Figure III.3.6 – *Percentage of indicators by category*

Table III.3.2 – *Technical indicators: recognition number, name, type of impact*

#	Technical Indicator Name	Type of impact
T1	%DOWNTIME	Direct
T2	%HOURS CORRECTIVE MAINTENANCE/TOT HOURS OF MAINTENANCE	Direct
T3	%HOURS PREVENTIVE MAINTENANCE/TOT HOURS OF MAINTENANCE	Direct
T4	AVAILABILITY OF THE MACHINE	Direct
T5	MECHANICAL EFFICIENCY OF THE LINE	Indirect
T6	MINIMUM NUMBER OF AVAILABLE SPARE PARTS	Direct
T7	MTBF	Direct
T8	MTTR	Direct
T9	MTTr (Mean Time To repair – specific for preventive maintenance actions)	Direct
T10	#FAILURES	Direct
T11	#INEFFICIENT MAINTENANCE INTERVENTIONS	Direct
T12	#PERFORMED MANITENANCE INTERVENTIONS/NUMBER OF PLANNED MAINTENANCE INTERVENTIONS	Direct
T13	#SEMI-MANUFACTURED ITEMS NON COMPLIANTS	Indirect
T14	OEE	Indirect
T15	OLE (Overall Line Effectiveness)	Indirect
T16	TIME BETWEEN MAINTENANCE REQUEST AND MAINTENANCE INTERVENTION	Direct

Table III.3.3 – *Technical indicators: occurrence frequency in each case*

	Case													
#ind.	**A**	**B**	**E1**	**E2**	**F**	**G1**	**G2**	**H**	**I**	**M**	**O**	**P**	**Q1**	**Q2**	**Tot.**
T1						X									1
T2			X												1
T3			X												1
T4												X			1
T5		X													1
T6													X		1
T7	X		X		X					X			X		5
T8	X		X		X			X	X	X		X	X		8
T9			X		X							X			3
T10			X							X	X				3
T11										X					1
T12													X		1
T13					X					X					2
T14			X		X					X	X				4
T15			X												1
T16										X					1

Table III.3.4 provides the economic indicators used by the stakeholders interviewed for the pilot survey, the associated recognition number, and the type of maintenance impact (direct/indirect) on each indicator.

Table III.3.5 reports the economic indicators defined in Table III.3.4 with their frequency of utilisation by each case. This view allows understanding the most used economic indicators.

Table III.3.4 – *Economic indicators: recognition number, name, type of impact*

#	**Economic Indicator Name**	**Type of impact**
EC1	BUDGET FOR MAINTENANCE ACTIVITIES	Direct
EC2	COST OF MAINTENANCE PER MACHINE	Direct
EC3	COSTS FOR WASTE TREATMENT OF PRODUCTION PROCESS	Indirect
EC4	COSTS OF ENERGY USED BY PRODUCTION PROCESS	Indirect
EC5	COSTS OF EXTERNAL MAINTENANCE	Direct
EC6	COSTS OF EXTERNAL TRAINING	Direct
EC7	COSTS OF LOST PRODUCTION FOR FAILURE	Direct
EC8	COSTS OF MAINTENANCE EMPLOYEES	Direct
EC9	COSTS OF PRODUCTION EMPLOYEES	Indirect
EC10	COSTS OF RECYCLED MATERIALS	Direct
EC11	COSTS OF REWORKING	Indirect
EC12	COSTS OF SPARE PARTS	Direct
EC13	COSTS OF STORAGE FOR SPARE PARTS AND TOOLS USED IN MAINTENANCE ACTIVITIES	Direct
EC14	INVESTMENTS IN ENERGY EFFICIENCY	Direct

Table III.3.5 – *Economic indicators: occurrence frequency in each case*

	Case														
#ind.	**A**	**B**	**E1**	**E2**	**F**	**G1**	**G2**	**H**	**I**	**M**	**O**	**P**	**Q1**	**Q2**	**Tot.**
EC1						X							X		2
EC2					X										1
EC3				X	X										2
EC4		X												X	2
EC5						X		X		X	X				4
EC6	X														1
EC7			X					X		X					3
EC8	X	X	X		X	X		X	X	X			X		9
EC9		X		X											2
EC10					X										1
EC11					X			X		X					3
EC12	X	X	X		X	X		X	X	X	X	X	X		11
EC13									X						1
EC14		X													1

Table III.3.6 provides the environmental indicators used by the stakeholders interviewed for the pilot survey, the associated recognition number, and the type of maintenance impact (direct/indirect) on each indicator.

Table III.3.7 reports the environmental indicators defined in Table III.3.6 with their frequency of utilisation by each case. This view allows understanding the most used environmental indicators.

Table III.3.6 – *Environmental indicators: recognition number, name, type of impact*

#	Environmental Indicator Name	Type of impact
EN1	AMOUNT OF WASTES GENERATED BY MAINTENANCE PROCESS	Direct
EN2	AMOUNT OF WASTES GENERATED BY PRODUCTION PROCESS	Indirect
EN3	ENERGY CONSUMPTION FOR PRODUCTION PROCESS	Indirect
EN4	ENERGY EFFICIENCY FOR PRODUCTION PROCESS	Indirect
EN5	MATERIALS USED FOR PRODUCTION PROCESS (auxiliary fluids, auxiliary materials, raw materials, semi-manufactured goods or parts)	Indirect
EN6	VOLUME OF RECORDED SIGNIFICANT SPILLS (i.e. accidental release of hazardous substances that can affect human health - land, vegetation, waterbodies and groundwater)	Indirect
EN7	VOLUME OF WATER WITHDRAWN FOR PRODUCTION PROCESS	Indirect

Table III.3.7 – *Environmental indicators: occurrence frequency in each case*

	Case													
#ind.	**A**	**B**	**E1**	**E2**	**F**	**G1**	**G2**	**H**	**I**	**M**	**O**	**P**	**Q1**	**Q2**	**Tot.**
EN1														X	1
EN2				X				X	X	X				X	5
EN3		X		X							X			X	4
EN4		X													1
EN5				X											1
EN6				X					X						2
EN7				X											1

Table III.3.8 provides the social indicators used by the stakeholders interviewed for the pilot survey, the associated recognition number, and the type of maintenance impact (direct/indirect) on each indicator.

Table III.3.9 reports the social indicators defined in Table III.3.8 with their frequency of utilisation by each case. This view allows understanding the most used social indicators.

Table III.3.8 – *Social indicators: recognition number, name, type of impact*

#	Social Indicator Name	Type of impact
S1	ABSENTEE RATE	Direct
S2	AVERAGE HOURS OF TRAINING PER MAINTENANCE EMPLOYEES (maintenance procedures, safety courses, upgrading skills, etc.)	Direct
S3	BONUS SALARY FOR GOOD MAINTENANCE EMPLOYEE PERFORMANCE	Direct
S4	CUSTOMER SATISFACTION (e.g. surveys…)	Indirect
S5	LOST WORKDAY RATE DUE TO MAINTENANCE ACCIDENTS	Direct
S6	#CUSTOMER COMPLIANTS CONCERNING A MANUFACTURING PRODUCT	Indirect
S7	PERSONAL PROTECTIVE EQUIPMENT	Direct
S8	PRODUCT QUALITY ASSURANCE AND MANAGEMENT: INCIDENTS OF PRODUCT RECALLS AND CUSTOMER COMPLIANTS AND RESOLUTION MET FROM THESE INCIDENTS	Indirect
S9	TYPE AND SCOPE OF TRAINING PROGRAMS PROVIDED BY MAINTENANCE FOR UPGRADING EMPLOYEES SKILLS	Direct
S10	TYPE OF INJURY AND INJURY RATE DUE TO MAINTENANCE ACTIVITIES	Direct

Table III.3.9 – *Social indicators: occurrence frequency in each case*

	Case													
#ind.	**A**	**B**	**E1**	**E2**	**F**	**G1**	**G2**	**H**	**I**	**M**	**O**	**P**	**Q1**	**Q2**	**Tot.**
S1						X									1
S2	X	X	X		X	X							X		6
S3						X									1
S4	X														1
S5						X									1
S6		X													1
S7												X			1
S8				X	X					X					3
S9		X									X	X	X		4
S10						X	X							X	3

Then, according to section III.2.1.3, it was asked if the aforementioned indicators are used for the continuous improvement and in which way.

The answers to this question were several, some more generic, others more specific.

Stakeholder A reported that indicators are essential for the continuous improvement and based on the indicator values, the development engineering of company takes decisions for future developments. Stakeholder B monitors indicators to understand the possible connection with the occurred failures or the quality/cost of the final product, and based on the indicator value, they propose investments or improvements activities in order to "change" the current value of the indicator in the future.

G1 and O stakeholders used kaizen for the continuous improvement. Stakeholder G1 explained that the company made available the indicator values through all the employees in order to share information, make them part of the organisation and more aware about indicator values, that intrinsically is a goal of the continuous improvement. G1 gave examples on the indicators used for the continuous improvement, such as the number of accidents, %downtime. In particular, the number of accidents are used for improving the maintenance procedures, for the awareness and the training of maintenance employees, but also for improving the plant design.

G2 and Q2 stakeholders, which belongs to environmental and safety area, reported that all indicators of their area were inserted in a general documentation for the evaluation of safety and environment system and for the definition of possible improvements. Some of these improvements can be related to maintenance area that affects environmental and safety indicators of such area due to direct and indirect maintenance impacts on these specific indicators.

Some stakeholders (E1, E2, F, H, I, M, and Q1), according to the indicator values, analyse them and the root causes that led to this value and then decide how to act in maintenance area and the improvements to make. For example, when there is a failure or a defect, through FMEA procedure, the company analyses the defect modes and the parameters to control in order to avoid defects or failures and choose the most appropriate type of maintenance employee according to his/her skills and level of training (case E1, E2). According to stakeholder E1 and F, the company area analysed the maintenance cost associated to different components in order to reduce such cost through proposal of design modification to component providers or grouping of maintenance interventions or investments in new components, which can reduce the cost associated to specific machine components. An example of continuous improvement through water and energy indicators related to the production process was done by E2. He realised that these indicator values increased due to failures and non-operation of the machines: the production process continued to consume energy and water even if it is not producing. Therefore, they set that after a fixed time of no-production, the machine has to be stopped to avoid useless energy and water consumption.

As reported by stakeholders I and P, the analysis of the indicators was respectively done through periodic reunion to decide the improvement actions to undertake or through management software that automatically suggest improvements.

Concerning the questions dealing with the collection and the analysis of data needed for the calculation of the indicators, the stakeholders reported who collects and analyses the data, and how and when the collection and the analysis are performed.

In particular, the data were collected by maintainers or other employees and reported on specific papers (A, E1, G2, H, I, O, P, Q2) or on specific devices (B, E2, F, G1, M, P, Q1, Q2); otherwise the data are automatically collected by software and devices. The difference on the ways to collect data depends both on the data type (if data are related to maintenance intervention or to the system to be maintained or other systems) and on the structure and the automation level of the organisation to which the interviewee belongs. Moreover, the data are collected daily (B, E1, E2, F, G1, H, M, P, Q1), or weekly (G1), or monthly (G1, Q2), or based on a specific condition/event (F, G2).

In all the cases of the pilot survey, the data were analysed by a specific person: an analyst (A, H, I, and M), or an individual manager of the organisation (B, G1, H, M, Q1, and Q2), or the employees (O), or a controller of different plants of the same organisation (B). In other cases, a team reunion with different stakeholders of the company (G1, G2, P, and Q2) or a team reunion with bodies external to the company (Q2) to discuss and analyse data are organised. Stakeholder F reported that only if some monitored parameters are out of control, the data analysis was performed. The data analysis was performed daily (B, E1, E2, G1, and P), or weekly (B, G1), or monthly (B, G1, O, Q1, and Q2), or six-monthly (Q2), or annually

(G2). In the future, stakeholders E1, E2 and F aim to analyse data automatically through the enabling technologies 4.0.

Finally, it was asked if the company area, to which the stakeholder belongs, intends to introduce new indicators to measure maintenance impacts and it was discussed with the interviewee the possibility or the convenience to introduce new indicators for the measurement of direct or indirect maintenance impacts. The results show that E1, F, G1, P, and Q1 do not intend to introduce new indicators in the future; some of them are convinced that they monitor already too much indicators. Stakeholder E2 and M aim to respectively eliminate the indicator related to the number of failures (because in the company they aim at zero failures and then this indicator won't be necessary) and the number of incidents of non-compliant products (because it is not necessary to monitor the number of incidents but rather the value of each incident of non-compliance). Instead, stakeholders H and M aim to introduce new indicators but they did not specify which type of indicators, while stakeholder B would introduce the economic indicator related to the cost for the different type of production lines. Some technical indicators would be integrated by several stakeholders: the stakeholder B aims to introduce the MTBF and the number of failures per line and per machine (fixing a target); the stakeholder I the repetitiveness of the intervention; the stakeholder O the MTTR and the MTBF.

After a long discussion with stakeholder E2 on the sustainability problems of his plant, he agreed that should be included four environmental indicators: chemical products consumption caused by machine failures impacts, energy consumption caused by machine failures impacts, resources consumption caused by machine failures impacts, and water consumption caused by machine failures impacts. The stakeholder A is realising in the last years the relevance of maintenance skills and he aims to introduce a new indicators related to this social aspect. Stakeholder G2 is mainly focused on safety aspects and he would collect data related to incidents of "missing injuries", namely all the occasions in which an accident could occur. Instead, stakeholder Q2 is more interested to ergonomic aspects and he would introduce indicators both to evaluate the time of response to a stakeholder request to fix ergonomic problems and number of requests for ergonomic issues.

Moreover, during the discussion, some stakeholders highlighted that only recently some sustainability indicators were introduced in their companies, becoming aware about the necessity to measure the sustainable performance of organisations. However, it appears that most of the stakeholders, even if they belong to well-structured and innovative companies, are not aware of how much the maintenance area affect sustainability aspects. Therefore, it was discussed about the necessity to introduce of more specific indicators for measuring maintenance impacts on sustainability.

III.4 Result Discussion

The results of the interviews allowed reaching two goals.

1) A first step towards the validation of the framework.

2) Unveiling the spread of measurement of maintenance impacts on sustainability.

1) First of all, the analysis of the information gathered through the interview allowed confirming the main elements within the proposed framework, achieving a first step of validation of the conceptual framework. It was a “first step of validation” because the framework was not showed during the interviews to the organisations but, through the ad-hoc questions, the main contents were analysed in order to verify its validity.

Thanks to the interviews of several stakeholders, the applicability of the conceptual framework was verified both in terms of contents (a) and of use of the framework (b).

a) Through the questions related to the type of indicators used by the stakeholders for measuring maintenance impacts and to the indicators that they would introduce in the near future, it was possible to confirm that the sustainability indicators listed by the interviewees are included in the ones presented in the framework. This gives confirmation of the exhaustiveness of the content of the framework. Furthermore, the framework includes a detailed view of indicators in the three pillars of sustainability affected by maintenance processes, confirming that it can “suggest” to stakeholders, based on their “gaps”, the sustainability measures in relation with maintenance to take into account.

b) Through the interviews, it was possible to verify and validate the consistency with respect to the use of the framework, namely the several “ways of navigation” based on the stakeholders’ needs. In fact, based on the interviewed stakeholders, different indicators were evaluated and, therefore, different areas of the framework were explored. It was then validated that, based on the stakeholders’ requests, the framework can be capable to guide them in different ways, satisfying the needs, showing the maintenance impacts on his/her reference system and on sustainability pillars of interest, selecting different indicators for evaluating such impacts. This confirms the framework’s flexibility that can support different “ways of navigation”, guiding stakeholders of different business areas with different requests.

Therefore, through the discussion with several stakeholders holding positions in different areas of organisations, it was confirmed that the framework could support them in two ways. First, to be more aware about the relationships between maintenance processes and sustainability aspects, then, it can guide them to define and select the indicators of interest for assessing maintenance impacts on sustainability and then to undertake continuous improvement actions.

2) Empirical evidence on current practices of maintenance performance measurement in production companies is contextually unveiled. In particular, through the pilot survey, it was unveiled the level of awareness of stakeholders about the relationships between maintenance processes and sustainability aspects and the spread of measurement of maintenance impacts on sustainability.

In particular, from one hand, there are stakeholders who don't use indicators to measure maintenance performance and impacts. From another hand, there are stakeholders who use indicators to measure maintenance impacts, but with different levels of awareness related to the relationship between maintenance and sustainability aspects. These stakeholders can be mainly divided in two classes: the ones who measure maintenance impacts through conventional technical indicators but are not aware about maintenance impacts on all the three pillars of sustainability and the ones who are becoming aware about maintenance impacts on sustainability but needs to be guided for the definition of indicators. Generally, empirical evidence showed that stakeholders who belong to maintenance area are mainly focused on technical and economic aspects, while stakeholders holding position in environmental, quality, and safety areas are becoming aware about maintenance impacts on environmental and social aspects. However, all of them need a guide to become more aware about maintenance impacts on sustainability and to define sustainability indicators to measure such impacts.

Anyway, it is evident that even if most of the interviewed stakeholders are aware about the sustainability goals that their companies and areas have to reach in order to cope with the challenges imposed by today's competitive environment, they have a restrictive view of their business function. Therefore, they are not aware about maintenance impacts on general sustainability goals. Moreover, the interview results showed that, often, the main obstacle to achieve sustainability goals is, first, the way of thinking of the stakeholders.

The conceptual framework can provide to stakeholders a holistic view of maintenance impacts in the whole organisation up to the customer and on all the three pillars of sustainability, increasing their awareness about non-negligible maintenance impacts. Moreover, it can support different stakeholders, guiding them in the selection of the indicators to measure and monitor in order to contribute to the achievement of sustainable goals of organisations.

Based on the lessons learnt from the analysis of the case studies, we believe that organisations have to get more and more aware of the importance of addressing maintenance as set of processes that, from one hand, has to sustain the equipment/assets during their operation in order to guarantee the compliance of the production process, of the manufactured products and to reduce industrial impacts on economy, society, and surrounding environment and, on the other hand, itself has to be a sustainable business function in order to limit flows and impacts generated during maintenance activities.

Chapter IV
IV. Conclusions, contributions, and suggestions for future research

IV.1 Conclusion and contribution of the thesis

The first objective of this research thesis was to discuss about the relationship between maintenance and sustainability in the industrial context, a relatively new research area that is attracting more and more attention in the last decade. However, an exhaustive literature review in this research area was not found. Therefore, a literature review on 'maintenance and sustainability' was provided in Chapter I. The literature review was conducted through a 'scoping' literature review methodology that, on the contrary of conventional reviews based on the author knowledge perspective, follows a protocol minimizing the subjectivity. The studies selected for the analysis have been classified according to specific research clusters and the main gaps found have been highlighted in section I.5. Several research challenges (*RCs*) were consequently underlined in section I.5 and the first one, *RC1,* was addressed in Chapter II.

The second objective of this research thesis was to provide an original scientific contribution to the scientific issues identified in the research challenge *RC1*. Therefore, Chapter II provides the identification of maintenance impacts in the organisation up to the customer on the three pillars of sustainability through the definition of the sustainability indicators of different systems (MS, TS, and TSO) directly and indirectly affected by maintenance processes. A conceptual framework for measuring maintenance impacts on sustainability including the sustainability indicators affected by maintenance processes was developed and proposed in Chapter II as a scientific contribution to *RC1*. The proposed framework is general and holistic and can guide different types of stakeholders in different industrial contexts to be more aware about maintenance impacts on sustainability and to select the sustainability indicators of interest to measure and monitor maintenance performance/activities. The stakeholders can 'navigate' on the framework based on their needs, therefore according to the sustainability pillars of interest, the maintenance processes and the systems of interest and, therefore, select the indicators from the tables provided in appendix based on their objectives.

The third objective of this research thesis was to validate the content of the conceptual framework and contextually, to unveil the spread of measurement of maintenance impacts on sustainability in industrial contexts in order to identify the main gaps in industrial contexts. Chapter III provides the results of a pilot survey study conducted to reach this objective. In particular, an ad hoc interview was submitted to eighteen stakeholders of fifteen organisations of the south of Italy. The considered companies belonged to different industrial sectors to have a general overview and validating the framework as a guide for integration in any production companies of measurement of maintenance impacts on sustainability.

The main contributions of this research are:

- the definition of the concept of 'sustainable maintenance' (introductive section);
- the development of a scoping literature review in the research area of 'maintenance and sustainability in industrial context' (chapter I);
- the identification of gaps and research challenges in the research area (section I.5);
- the identification of maintenance impacts in the organisation up to the customer in the three pillars of sustainability through the definition and formalisation of sustainability indicators of different systems affected by maintenance processes (chapter II);
- the development of a holistic conceptual framework for measuring maintenance impacts on sustainability, applicable to a wide range of industrial contexts (chapter II);
- the development of a pilot survey study through the submission of an interview defined ad hoc for validating the content of the framework and for unveiling the current spread of measurement of maintenance impacts on sustainability in industries (chapter III).

Considering the social relevance of the topic of sustainable manufacturing in the long-term, therefore, looking at the impacts of maintenance function on sustainability goals of companies, the topic related to the relationship between maintenance and sustainability should be promoted in order to contribute to scientific discussion as well as to bring awareness from maintenance departments to other internal and external stakeholders. In that way, recent efforts have been done by several researchers in such scope for contributing to the scientific research. However, the impacts of maintenance processes on sustainability in the whole organisation up to the customer have not clearly been defined in literature, and the relationship between the performance of maintenance processes and sustainability indicators have not exhaustively defined and formalised. This thesis fills this gap, presenting a wide literature review and proposing a conceptual framework for measuring maintenance impacts on sustainability. Therefore, this work provides a deeper knowledge of maintenance impacts on economic, environmental and social sustainability and on the indicators that could be used for measuring these impacts, contributing to the goal of bringing awareness in the scope of 'maintenance and sustainability' in the industrial context.

IV.2 Suggestions for future research

This thesis gives rise to several research opportunities. Suggestions (*S*) for future research are therefore reported below. They are listed according to the horizon to which they could be developed in the short, medium, and long term, underlined in brackets at the end of each suggestion S.

S1. A demonstration of the feasibility and applicability of the conceptual framework, therefore a first step towards its validation, was achieved through the submission to several and different stakeholders of an ad hoc interview. The questions of the interview were structured in a way that the content of the framework was addressed. However, the framework was not showed to the stakeholders during the interview. A further research involves a 'completion' of the validation through the presentation of the content of the framework to industrial and academic experts in the field of maintenance and sustainability (e.g. conducting a Delphi Analysis) in order to definitively validate the framework or integrate new sustainability indicators. During future focus expert groups, new findings can be find. [*Short Term*]

S2. A pilot survey study through the submission of an interview to a sample of eighteen stakeholders was also conducted in order to unveil the spread of measurement of maintenance impacts on sustainability. The interview can be submitted to more stakeholders of companies at national (in other regions of Italy) and international level (e.g. in France or elsewhere) in order to have a wide view of the current spread of measurement of maintenance impacts on sustainability and to implement statistical analysis. [*Short Term*]

S3. The framework involves many sustainability indicators (of different systems related to a generic organisation) affected by maintenance processes, that can be selected based on the stakeholders' needs. A further step should define the formalised relationships and rules among indicators belonging to economic, environmental, and social sustainability pillars (and the technical ones) and to different systems in order to guide stakeholders in an 'automatic way' on the indicators that need to be monitored according to their needs. [*Medium Term*]

S4. According to the *RC2* already identified in section I.5 but not addressed in this thesis, the integration of indicators and their relationships and rules in maintenance decision-making models (e.g. through a casual loop diagram - system dynamics approach) will allow to measure maintenance impacts on sustainability, respect sustainability targets fixed by the stakeholders of organisations while improve other indicators as well. [*Medium Term*]

S5. The framework provides many sustainability indicators to measure maintenance impacts on sustainability. However, some stakeholders could be interested in one single measure of sustainability performance of their maintenance activities. A further research step should concern the evaluation of a single sustainable indicator (a composite index) through an aggregation operator of the several sustainability indicators. Since several indicators might be interacting, e.g. having some overlapping on the knowledge they provide, a tool such as Choquet integral could be used. [*Medium Term*]

S6. According to the *RC3* already identified in section I.5 but not addressed in this thesis, the enabling technologies of the fourth industrial revolution should be investigated and integrated in maintenance models, strategies and policies for contributing to a sustainable maintenance management. For example, through the collection/measurement of the real-time data related to parameters to monitor and data analytics, the enabling technologies can contribute to the development of a sustainable maintenance management. These technologies could be evaluated thanks to the models proposed in *S4*. [*Long Term*]

S7. Once the validation of the framework will be completed (*S1*), it can contribute to the development of a future ISO standard related to the measurement of maintenance impacts on sustainability in organisations. [*Long Term*]

Appendix

Table A.1 – *Cube of knowledge: economic indicators of maintenance system affected by MAN, DOC, MRQ, OPT, DTA, SER maintenance processes*

		MAINTENANCE SYSTEM – DIRECT IMPACT
	Sub-Category	**MAINTENANCE PROCESSES: MAN – Manage maintenance; DOC – Deliver operational documentation; MRQ – Deliver maintenance requirements during items design & modification; OPT – Improve the results; DTA – Manage data; SER – Provide maintenance services**
ECONOMIC CATEGORY	***Economic Performance***	• Costs associated with EHS (Environment, Health, and Safety) compliance (*e.g. fines, liabilities, worker compensation, cost/depreciation of control equipment, remediation cost, labour cost*) of maintenance activities • Costs for acquisition of spare parts, materials, consumables • Costs of energy used by maintenance processes (*e.g. tools, means of transports, parts*) • Costs of maintenance employees • Ratio of actual labour hours to planned labour hours in performing a maintenance operation
	Investments	

Table A.2 – *Cube of knowledge: environmental indicators of maintenance system affected by MAN, DOC, MRQ, OPT, DTA, SER maintenance processes (pt1)*

		MAINTENANCE SYSTEM – DIRECT IMPACT
	Sub-Category	**MAINTENANCE PROCESSES: MAN – Manage maintenance; DOC – Deliver operational documentation; MRQ – Deliver maintenance requirements during items design & modification; OPT – Improve the results; DTA – Manage data; SER – Provide maintenance services**
ENVIRONMENTAL CATEGORY	***Effluents and Wastes***	• Amount of wastes generated by maintenance processes (*e.g. replaced items, used tools, lubricants, oils, documentation*) specified by waste type and disposal method (*i.e. hazardous and non-hazardous, recyclable, reusable, remanufacturable, disposable*) • Amount of waste water discharged by maintenance processes specified by quality (*e.g. eco-toxic, hazardous, treated, non-treated, reused*) and destination • Amount of WEEE produced by maintenance processes • Maintenance waste effects on the surface integrity of surrounding buildings and places

Table A.3 – *Cube of knowledge: environmental indicators of maintenance system affected by MAN, DOC, MRQ, OPT, DTA, SER maintenance processes (pt2)*

	Sub-Category	**MAINTENANCE SYSTEM – DIRECT IMPACT** **MAINTENANCE PROCESSES: MAN – Manage maintenance; DOC – Deliver operational documentation; MRQ – Deliver maintenance requirements during items design & modification; OPT – Improve the results; DTA – Manage data; SER – Provide maintenance services**
ENVIRONMENTAL CATEGORY	***Emissions***	• Direct GHG emissions: CO_2-eq due to electricity, heating, cooling and steam consumed by maintenance processes; transportation of materials, spare parts, and maintenance workers on the field. (*Gases included in the calculation are CO2, CH4, N2O, HFCs, PFCs, SF6, NF3, or all*). • Indirect GHG emissions: CO_2-eq due to purchased or acquired electricity, heating, cooling, and steam consumed by maintenance processes • GHG emissions intensity: ratio between absolute GHG emissions associated to maintenance processes and the organization-specific metric (*e.g. units of product of organization, production volume, size, #employees*) • Reduction of GHG emissions as a direct result of reduction initiatives taken by maintenance processes (*e.g. conversion and retrofitting of equipment used for maintenance activities*) • Ozone-depleting substances produced due to maintenance processes (*e.g. generated by air conditioners, solvents for cleaning, electronic equipment*) • Air emissions (such as NOX, SOX, POP (Persistent Organic Pollutants), VOC (Volatile Organic Compounds), HAP (Hazardous Air Pollutants), PM (Particulate Matter)) deriving from used chemicals, additives for lubricants, waste incineration, transportation and other, due to maintenance activities • Air quality within an organization and in its surrounding areas due to maintenance processes (smog, visibility, odour, GHG concentration, pollutant concentration, etc.)
	Energy Resource	• Energy consumption within an organization for maintenance processes (fuel, electricity, heating, cooling, steam) through vehicles, equipment and tools owned or controlled by organization • Energy intensity (A): ratio between absolute energy consumption for maintenance processes and the organization-specific metric (*e.g. units of product of organization, production volume, size, #employees*) • Reduction of energy consumption as a direct result of reduction initiatives taken by maintenance processes (*e.g. conversion and retrofitting of equipment used for maintenance activities*) • Energy emitted (*e.g. heat, vibration*) by maintenance processes • Energy intensity (B): Ratio between energy used by maintenance processes and energy available for these processes or the organization • Ratio of the actual energy consumed by maintenance processes to the theoretical energy needed for the maintenance processes
	Land Resource	• Maintenance waste effects on land quality (*e.g. indicated by surface integrity, soil nutrients and contaminants, non-fertile land*)
	Materials Resource	• Materials used for maintenance processes (*e.g. spare parts, documentation*) divided in renewable and non-renewable materials or with a breakdown on type of used materials (virgin, reused, recycled, remanufactured, repurposed) • Material intensity: ratio between the amount of materials needed for maintenance and the amount of materials used by maintenance • Quantity of auxiliary fluids used by maintenance processes (*e.g. cleaners, lubricants, oils, coolants*)

Table A.4 – *Cube of knowledge: environmental indicators of maintenance system affected by MAN, DOC, MRQ, OPT, DTA, SER maintenance processes (pt3)*

		MAINTENANCE SYSTEM – DIRECT IMPACT
	Sub-Category	**MAINTENANCE PROCESSES: MAN – Manage maintenance; DOC – Deliver operational documentation; MRQ – Deliver maintenance requirements during items design & modification; OPT – Improve the results; DTA – Manage data; SER – Provide maintenance services**
ENVIRONMENTAL CATEGORY	***Non-compliance with environmental laws and regulations***	
	Supplier environmental assessment	
	Water Resource	• Volume of water withdrawn for maintenance processes with a breakdown by the sources (*e.g. lakes, rivers, ground water, rainwater*)

Table A.5 – *Cube of knowledge: social indicators of maintenance system affected by MAN, DOC, MRQ, OPT, DTA, SER maintenance processes*

		MAINTENANCE SYSTEM – DIRECT IMPACT
	Sub-Category	**MAINTENANCE PROCESSES: MAN – Manage maintenance; DOC – Deliver operational documentation; MRQ – Deliver maintenance requirements during items design & modification; OPT – Improve the results; DTA – Manage data; SER – Provide maintenance services**
SOCIAL CATEGORY	***Customers***	
	Employees	• Number of employees in maintenance processes per unit of product or sales or revenues • Ratio between number of maintenance employee suggestions in quality, social and EHS performance and number of maintenance employees • Maintenance employee health and safety including: -type of injury and injury rate (*e.g. through #maintenance accidents requiring first aid*); -occupational disease rate; -lost workday rate due to maintenance accidents or diseases; -absentee rate; -work related fatalities arising from maintenance injury or occupational disease • Number of safety measures adopted and safety/fail-safe equipment installed due to maintenance employee suggestions, and improvements in safety performance from these suggestions
	Non-compliance with laws and regulations in the social and economic area	• Significant fines and non-monetary sanctions for non-compliance of maintenance activities with laws and regulations in the social and economic area
	Supplier social assessment	

Table A.6 – *Cube of knowledge: economic indicators of maintenance system affected by ACT maintenance process*

		MAINTENANCE SYSTEM – DIRECT IMPACT
	Sub-Category	**MAINTENANCE PROCESS: ACT – Act preventively or correctively on the item**
ECONOMIC CATEGORY	***Economic Performance***	• Costs associated with EHS (Environment, Health, and Safety) compliance (*e.g. fines, liabilities, worker compensation, cost/depreciation of control equipment, remediation cost, labour cost*) of maintenance activities • Costs for acquisition of spare parts, materials, consumables • Costs of energy used by maintenance processes (*e.g. tools, means of transports, parts*) • Costs of maintenance employees • Ratio of actual labour hours to planned labour hours in performing a maintenance operation
	Investments	

Table A.7 – *Cube of knowledge: environmental indicators of maintenance system affected by ACT maintenance process (pt1)*

		MAINTENANCE SYSTEM – DIRECT IMPACT
	Sub-Category	**MAINTENANCE PROCESS: ACT – Act preventively or correctively on the item**
ENVIRONMENTAL CATEGORY	***Effluents and Wastes***	• Amount of wastes generated by maintenance processes (*e.g. replaced items, used tools, lubricants, oils, documentation*) specified by waste type and disposal method (*i.e. hazardous and non-hazardous, recyclable, reusable, remanufacturable, disposable*) • Amount of waste water discharged by maintenance processes specified by quality (*e.g. eco-toxic, hazardous, treated, non-treated, reused*) and destination • Volume of recorded significant spills (*i.e. accidental release of hazardous substances that can affect human health, land, vegetation, water bodies, and ground water*) derived by maintenance processes • Transport of hazardous waste generated by maintenance activities • Amount of WEEE produced by maintenance processes • Maintenance waste effects on the surface integrity of surrounding buildings and places
	Emissions	• Direct GHG emissions: CO_2-eq due to electricity, heating, cooling and steam consumed by maintenance processes; transportation of materials, spare parts, and maintenance workers on the field. (*Gases included in the calculation are CO2, CH4, N2O, HFCs, PFCs, SF6, NF3, or all*). • Indirect GHG emissions: CO_2-eq due to purchased or acquired electricity, heating, cooling, and steam consumed by maintenance processes • GHG emissions intensity: ratio between absolute GHG emissions associated to maintenance processes and the organization-specific metric (*e.g. units of product of organization, production volume, size, #employees*) • Reduction of GHG emissions as a direct result of reduction initiatives taken by maintenance processes (*e.g. conversion and retrofitting of equipment used for maintenance activities*) • Ozone-depleting substances produced due to maintenance processes (*e.g. generated by air conditioners, solvents for cleaning, electronic equipment*) • Air emissions (such as NOX, SOX, POP (Persistent Organic Pollutants), VOC (Volatile Organic Compounds), HAP (Hazardous Air Pollutants), PM (Particulate Matter)) deriving from used chemicals, additives for lubricants, waste incineration, transportation and other, due to maintenance activities • Noise emissions for maintenance processes • Air quality within an organization and in its surrounding areas due to maintenance processes (smog, visibility, odour, GHG concentration, pollutant concentration, etc.)

Table A.8 – *Cube of knowledge: environmental indicators of maintenance system affected by ACT maintenance process (pt2)*

	Sub-Category	MAINTENANCE SYSTEM – DIRECT IMPACT MAINTENANCE PROCESS: ACT – Act preventively or correctively on the item
ENVIRONMENTAL CATEGORY	***Energy Resource***	• Energy consumption within an organization for maintenance processes (fuel, electricity, heating, cooling, steam) through vehicles, equipment and tools owned or controlled by organization • Energy intensity (A): ratio between absolute energy consumption for maintenance processes and the organization-specific metric (*e.g. units of product of organization, production volume, size, #employees*) • Reduction of energy consumption as a direct result of reduction initiatives taken by maintenance processes (*e.g. conversion and retrofitting of equipment used for maintenance activities*) • Energy emitted *(e.g. heat, vibration*) by maintenance processes • Energy intensity (B): Ratio between energy used by maintenance processes and energy available for these processes or the organization • Ratio of the actual energy consumed by maintenance processes to the theoretical energy needed for the maintenance processes
	Land Resource	• Maintenance waste effects on land quality (*e.g. indicated by surface integrity, soil nutrients and contaminants, non-fertile land*)
	Materials Resource	• Materials used for maintenance processes (*e.g. spare parts, documentation*) divided in renewable and non-renewable materials or with a breakdown on type of used materials (virgin, reused, recycled, remanufactured, repurposed) • Quantity of PBT (Persistent, Bioaccumulative and Toxic) chemicals used due to maintenance processes • Material intensity: ratio between the amount of materials needed for maintenance and the amount of materials used by maintenance • Quantity of auxiliary fluids used by maintenance processes (*e.g. cleaners, lubricants, oils, coolants*)
	Non-compliance with environmental laws and regulations	• Significant fines and non-monetary sanctions for non-compliance of maintenance processes with environmental laws and regulations
	Supplier environmental assessment	
	Water Resource	• Volume of water withdrawn for maintenance processes with a breakdown by the sources (*e.g. lakes, rivers, ground water, rainwater*)

Table A.9 – *Cube of knowledge: social indicators of maintenance system affected by ACT maintenance process*

		MAINTENANCE SYSTEM – DIRECT IMPACT
	Sub-Category	**MAINTENANCE PROCESS: ACT – Act preventively or correctively on the item**
SOCIAL CATEGORY	***Customers***	
	Employees	• Number of employees in maintenance processes per unit of product or sales or revenues • Ratio between number of maintenance employee suggestions in quality, social and EHS performance and number of maintenance employees • Maintenance employee health and safety including: -type of injury and injury rate (*e.g. through #maintenance accidents requiring first aid*); -occupational disease rate; -lost workday rate due to maintenance accidents or diseases; -absentee rate; -work related fatalities arising from maintenance injury or occupational disease • Maintenance employees with high incidence or high risk of diseases related to their occupation • Number of safety measures adopted and safety/fail-safe equipment installed due to maintenance employee suggestions, and improvements in safety performance from these suggestions
	Non-compliance with laws and regulations in the social and economic area	• Significant fines and non-monetary sanctions for non-compliance of maintenance activities with laws and regulations in the social and economic area
	Supplier social assessment	

Table A.10 – *Cube of knowledge: economic indicators of maintenance system affected by IMP maintenance process*

	Sub-Category	MAINTENANCE SYSTEM – DIRECT IMPACT MAINTENANCE PROCESS: IMP – Improve the items
ECONOMIC CATEGORY	***Economic Performance***	• Costs associated with EHS (Environment, Health, and Safety) compliance (*e.g. fines, liabilities, worker compensation, cost/depreciation of control equipment, remediation cost, labour cost*) of maintenance activities • Costs for acquisition of spare parts, materials, consumables • Costs of energy used by maintenance processes (*e.g. tools, means of transports, parts*) • Costs of maintenance employees • Ratio of actual labour hours to planned labour hours in performing a maintenance operation
	Investments	• Investments in energy efficiency instruments and initiatives taken by maintenance processes • Investments and expenditures in scientific research and experimental development (R&D), e.g. for new innovative technologies, taken by maintenance processes

Table A.11 – *Cube of knowledge: environmental indicators of maintenance system affected by IMP maintenance process (pt1)*

	Sub-Category	MAINTENANCE SYSTEM – DIRECT IMPACT MAINTENANCE PROCESS: IMP – Improve the items
ENVIRONMENTAL CATEGORY	***Effluents and Wastes***	• Amount of wastes generated by maintenance processes (*e.g. replaced items, used tools, lubricants, oils, documentation*) specified by waste type and disposal method (*i.e. hazardous and non-hazardous, recyclable, reusable, remanufacturable, disposable*) • Amount of waste water discharged by maintenance processes specified by quality (*e.g. eco-toxic, hazardous, treated, non-treated, reused*) and destination • Amount of WEEE produced by maintenance processes • Maintenance waste effects on the surface integrity of surrounding buildings and places
	Emissions	• Direct GHG emissions: CO_2-eq due to electricity, heating, cooling and steam consumed by maintenance processes; transportation of materials, spare parts, and maintenance workers on the field. (*Gases included in the calculation are CO2, CH4, N2O, HFCs, PFCs, SF6, NF3, or all*). • Indirect GHG emissions: CO_2-eq due to purchased or acquired electricity, heating, cooling, and steam consumed by maintenance processes • GHG emissions intensity: ratio between absolute GHG emissions associated to maintenance processes and the organization-specific metric (*e.g. units of product of organization, production volume, size, #employees*) • Reduction of GHG emissions as a direct result of reduction initiatives taken by maintenance processes (*e.g. conversion and retrofitting of equipment used for maintenance activities*) • Ozone-depleting substances produced due to maintenance processes (*e.g. generated by air conditioners, solvents for cleaning, electronic equipment*) • Air emissions (such as NOX, SOX, POP (Persistent Organic Pollutants), VOC (Volatile Organic Compounds), HAP (Hazardous Air Pollutants), PM (Particulate Matter)) deriving from used chemicals, additives for lubricants, waste incineration, transportation and other, due to maintenance activities • Air quality within an organization and in its surrounding areas due to maintenance processes (smog, visibility, odour, GHG concentration, pollutant concentration, etc.)

Table A.12 – *Cube of knowledge: environmental indicators of maintenance system affected by IMP maintenance process (pt2)*

		MAINTENANCE SYSTEM – DIRECT IMPACT
	Sub-Category	**MAINTENANCE PROCESS: IMP – Improve the items**
ENVIRONMENTAL CATEGORY	***Energy Resource***	• Energy consumption within an organization for maintenance processes (fuel, electricity, heating, cooling, steam) through vehicles, equipment and tools owned or controlled by organization • Energy intensity (A): ratio between absolute energy consumption for maintenance processes and the organization-specific metric (*e.g. units of product of organization, production volume, size, #employees*) • Reduction of energy consumption as a direct result of reduction initiatives taken by maintenance processes (*e.g. conversion and retrofitting of equipment used for maintenance activities*) • Energy emitted *(e.g. heat, vibration*) by maintenance processes • Energy intensity (B): Ratio between energy used by maintenance processes and energy available for these processes or the organization • Number of initiatives implemented by maintenance process for energy-efficiency improvements (*e.g. initiatives on the used tools*) • Number of initiatives implemented by maintenance process for indirect energy-efficiency improvements (*e.g. initiatives on the equipment to be maintained)* • Ratio of the actual energy consumed by maintenance processes to the theoretical energy needed for the maintenance processes
	Land Resource	• Maintenance waste effects on land quality (*e.g. indicated by surface integrity, soil nutrients and contaminants, non-fertile land*)
	Materials Resource	• Materials used for maintenance processes (*e.g. spare parts, documentation*) divided in renewable and non-renewable materials or with a breakdown on type of used materials (virgin, reused, recycled, remanufactured, repurposed) • Material intensity: ratio between the amount of materials needed for maintenance and the amount of materials used by maintenance • Quantity of auxiliary fluids used by maintenance processes (*e.g. cleaners, lubricants, oils, coolants*)
	Non-compliance with environmental laws and regulations	• Significant fines and non-monetary sanctions for non-compliance of maintenance processes with environmental laws and regulations
	Supplier environmental assessment	
	Water Resource	• Volume of water withdrawn for maintenance processes with a breakdown by the sources (*e.g. lakes, rivers, ground water, rainwater*)

Table A.13 – *Cube of knowledge: social indicators of maintenance system affected by IMP maintenance process*

<table>
<tr><td></td><td></td><td>MAINTENANCE SYSTEM – DIRECT IMPACT</td></tr>
<tr><td></td><td>Sub-Category</td><td>MAINTENANCE PROCESS: IMP – Improve the items</td></tr>
<tr><td rowspan="4">SOCIAL CATEGORY</td><td>Customers</td><td></td></tr>
<tr><td>Employees</td><td>• Number of employees in maintenance processes per unit of product or sales or revenues
• Ratio between number of maintenance employee suggestions in quality, social and EHS performance and number of maintenance employees
• Maintenance employee health and safety including: -type of injury and injury rate (e.g. through #maintenance accidents requiring first aid); -occupational disease rate; -lost workday rate due to maintenance accidents or diseases; -absentee rate; -work related fatalities arising from maintenance injury or occupational disease
• Number of safety measures adopted and safety/fail-safe equipment installed due to maintenance employee suggestions, and improvements in safety performance from these suggestions</td></tr>
<tr><td>Non-compliance with laws and regulations in the social and economic area</td><td>• Significant fines and non-monetary sanctions for non-compliance of maintenance activities with laws and regulations in the social and economic area</td></tr>
<tr><td>Supplier social assessment</td><td></td></tr>
</table>

Table A.14 – *Cube of knowledge: economic indicators of maintenance system affected by HSE maintenance process*

	Sub-Category	MAINTENANCE SYSTEM – DIRECT IMPACT MAINTENANCE PROCESS: HSE – Guarantee health and safety to individuals and preserve environment in maintenance
ECONOMIC CATEGORY	*Economic Performance*	• Costs associated with EHS (Environment, Health, and Safety) compliance (*e.g. fines, liabilities, worker compensation, cost/depreciation of control equipment, remediation cost, labour cost*) of maintenance activities • Costs for acquisition of spare parts, materials, consumables • Costs of energy used by maintenance processes (*e.g. tools, means of transports, parts*) • Costs of maintenance employees • Costs for managing maintenance employee responsibilities in reporting or assessing risks • Ratio of actual labour hours to planned labour hours in performing a maintenance operation
	Investments	

Table A.15 – *Cube of knowledge: environmental indicators of maintenance system affected by HSE maintenance process (pt1)*

	Sub-Category	MAINTENANCE SYSTEM – DIRECT IMPACT MAINTENANCE PROCESS: HSE – Guarantee health and safety to individuals and preserve environment in maintenance
ENVIRONMENTAL CATEGORY	*Effluents and Wastes*	• Amount of wastes generated by maintenance processes (*e.g. replaced items, used tools, lubricants, oils, documentation*) specified by waste type and disposal method (*i.e. hazardous and non-hazardous, recyclable, reusable, remanufacturable, disposable*) • Amount of waste water discharged by maintenance processes specified by quality (*e.g. eco-toxic, hazardous, treated, non-treated, reused*) and destination • Volume of recorded significant spills (*i.e. accidental release of hazardous substances that can affect human health, land, vegetation, water bodies, and ground water*) derived by maintenance processes • Amount of WEEE produced by maintenance processes • Maintenance waste effects on the surface integrity of surrounding buildings and places
	Emissions	• Direct GHG emissions: CO_2-eq due to electricity, heating, cooling and steam consumed by maintenance processes; transportation of materials, spare parts, and maintenance workers on the field. (*Gases included in the calculation are CO2, CH4, N2O, HFCs, PFCs, SF6, NF3, or all*). • Indirect GHG emissions: CO_2-eq due to purchased or acquired electricity, heating, cooling, and steam consumed by maintenance processes • GHG emissions intensity: ratio between absolute GHG emissions associated to maintenance processes and the organization-specific metric (*e.g. units of product of organization, production volume, size, #employees*) • Reduction of GHG emissions as a direct result of reduction initiatives taken by maintenance processes (*e.g. conversion and retrofitting of equipment used for maintenance activities*) • Ozone-depleting substances produced due to maintenance processes (*e.g. generated by air conditioners, solvents for cleaning, electronic equipment*) • Air emissions (such as NOX, SOX, POP (Persistent Organic Pollutants), VOC (Volatile Organic Compounds), HAP (Hazardous Air Pollutants), PM (Particulate Matter)) deriving from used chemicals, additives for lubricants, waste incineration, transportation and other, due to maintenance activities • Air quality within an organization and in its surrounding areas due to maintenance processes (smog, visibility, odour, GHG concentration, pollutant concentration, etc.)

Table A.16 – *Cube of knowledge: environmental indicators of maintenance system affected by HSE maintenance process (pt2)*

		MAINTENANCE SYSTEM – DIRECT IMPACT
	Sub-Category	**MAINTENANCE PROCESS: HSE – Guarantee health and safety to individuals and preserve environment in maintenance**
ENVIRONMENTAL CATEGORY	***Energy Resource***	• Energy consumption within an organization for maintenance processes (fuel, electricity, heating, cooling, steam) through vehicles, equipment and tools owned or controlled by organization • Energy intensity (A): ratio between absolute energy consumption for maintenance processes and the organization-specific metric (*e.g. units of product of organization, production volume, size, #employees*) • Reduction of energy consumption as a direct result of reduction initiatives taken by maintenance processes (*e.g. conversion and retrofitting of equipment used for maintenance activities*) • Energy emitted *(e.g. heat, vibration*) by maintenance processes • Energy intensity (B): Ratio between energy used by maintenance processes and energy available for these processes or the organization • Ratio of the actual energy consumed by maintenance processes to the theoretical energy needed for the maintenance processes
	Land Resource	• Maintenance waste effects on land quality (*e.g. indicated by surface integrity, soil nutrients and contaminants, non-fertile land*)
	Materials Resource	• Materials used for maintenance processes (*e.g. spare parts, documentation*) divided in renewable and non-renewable materials or with a breakdown on type of used materials (virgin, reused, recycled, remanufactured, repurposed) • Material intensity: ratio between the amount of materials needed for maintenance and the amount of materials used by maintenance • Quantity of auxiliary fluids used by maintenance processes (*e.g. cleaners, lubricants, oils, coolants*)
	Non-compliance with environmental laws and regulations	• Significant fines and non-monetary sanctions for non-compliance of maintenance processes with environmental laws and regulations
	Supplier environmental assessment	
	Water Resource	• Volume of water withdrawn for maintenance processes with a breakdown by the sources (e.g. lakes, rivers, ground water, rainwater)

Table A.17 – *Cube of knowledge: social indicators of maintenance system affected by HSE maintenance process*

	Sub-Category	**MAINTENANCE SYSTEM – DIRECT IMPACT** **MAINTENANCE PROCESS: HSE – Guarantee health and safety to individuals and preserve environment in maintenance**
SOCIAL CATEGORY	***Customers***	
	Employees	• Number of employees in maintenance processes per unit of product or sales or revenues • Ratio between number of maintenance employee suggestions in quality, social and EHS performance and number of maintenance employees • Revitalization of maintenance employee suggestions for improvement and specific effort periods (*e.g. one month, one week a month*) • %maintenance employees trained in basic sustainability concepts and/or current sustainability initiatives • Skill management programs provided by maintenance processes • %maintenance employees who report complete job satisfaction *(e.g. through use of questionnaire, surveys*) • Number or % maintenance employees empowered with the knowledge to make safer choices for themselves and coach their peers to do the same • Maintenance employee health and safety including: -type of injury and injury rate (*e.g. through #maintenance accidents requiring first aid*); -occupational disease rate; -lost workday rate due to maintenance accidents or diseases; -absentee rate; -work related fatalities arising from maintenance injury or occupational disease • Diffusion of work-related illness: increase/decrease in number of maintenance employees affected by work-related illness • Number of safety measures adopted by maintenance processes, safety/fail-safe equipment installed, and improvements in safety performance from these measures • Number of safety measures adopted and safety/fail-safe equipment installed due to maintenance employee suggestions, and improvements in safety performance from these suggestions • Education, training, counselling, prevention, and risk-control programs in place to assist maintenance workforce members and their families regarding serious diseases • Education, training, counselling, prevention, and employee empowerment to limit the risk of work place injuries
	Non-compliance with laws and regulations in the social and economic area	• Significant fines and non-monetary sanctions for non-compliance of maintenance activities with laws and regulations in the social and economic area
	Supplier social assessment	

Table A.18 – *Cube of knowledge: economic indicators of maintenance system affected by BUD maintenance process*

	Sub-Category	MAINTENANCE SYSTEM – DIRECT IMPACT MAINTENANCE PROCESS: BUD - Maintenance budget of items
ECONOMIC CATEGORY	***Economic Performance***	• Costs associated with EHS (Environment, Health, and Safety) compliance (*e.g. fines, liabilities, worker compensation, cost/depreciation of control equipment, remediation cost, labour cost*) of maintenance activities • Costs for acquisition of spare parts, materials, consumables • Costs of energy used by maintenance processes (*e.g. tools, means of transports, parts*) • Costs for purchase of maintenance tools • Costs of maintenance employees • Costs for hiring new maintenance personnel • Costs for maintenance waste treatment • Costs of storage for spare parts and tools used in maintenance activities • Costs for managing maintenance employee responsibilities in reporting or assessing risks • Costs to recycle spare parts or WEEE (Waste Electric and Electronic Equipment) • Ratio of actual labour hours to planned labour hours in performing a maintenance operation
	Investments	• Investments in energy efficiency instruments and initiatives taken by maintenance processes • Investments and expenditures in scientific research and experimental development (R&D), e.g. for new innovative technologies, taken by maintenance processes • Investments in development of infrastructure and services supported

Table A.19 – *Cube of knowledge: environmental indicators of maintenance system affected by BUD maintenance process (pt1)*

	Sub-Category	MAINTENANCE SYSTEM – DIRECT IMPACT MAINTENANCE PROCESS: BUD - Maintenance budget of items
ENVIRONMENTAL CATEGORY	***Effluents and Wastes***	• Amount of wastes generated by maintenance processes (*e.g. replaced items, used tools, lubricants, oils, documentation*) specified by waste type and disposal method (*i.e. hazardous and non-hazardous, recyclable, reusable, remanufacturable, disposable*) • Amount of waste water discharged by maintenance processes specified by quality (*e.g. eco-toxic, hazardous, treated, non-treated, reused*) and destination • Amount of WEEE produced by maintenance processes • Maintenance waste effects on the surface integrity of surrounding buildings and places

Table A.20 – *Cube of knowledge: environmental indicators of maintenance system affected by BUD maintenance process (pt2)*

		MAINTENANCE SYSTEM – DIRECT IMPACT
	Sub-Category	**MAINTENANCE PROCESS: BUD - Maintenance budget of items**
ENVIRONMENTAL CATEGORY	***Emissions***	• Direct GHG emissions: CO_2-eq due to electricity, heating, cooling and steam consumed by maintenance processes; transportation of materials, spare parts, and maintenance workers on the field. (*Gases included in the calculation are CO2, CH4, N2O, HFCs, PFCs, SF6, NF3, or all*). • Indirect GHG emissions: CO_2-eq due to purchased or acquired electricity, heating, cooling, and steam consumed by maintenance processes • GHG emissions intensity: ratio between absolute GHG emissions associated to maintenance processes and the organization-specific metric (*e.g. units of product of organization, production volume, size, #employees*) • Reduction of GHG emissions as a direct result of reduction initiatives taken by maintenance processes (*e.g. conversion and retrofitting of equipment used for maintenance activities*) • Ozone-depleting substances produced due to maintenance processes (*e.g. generated by air conditioners, solvents for cleaning, electronic equipment*) • Air emissions (such as NOX, SOX, POP (Persistent Organic Pollutants), VOC (Volatile Organic Compounds), HAP (Hazardous Air Pollutants), PM (Particulate Matter)) deriving from used chemicals, additives for lubricants, waste incineration, transportation and other, due to maintenance activities Air quality within an organization and in its surrounding areas due to maintenance processes (smog, visibility, odour, GHG concentration, pollutant concentration, etc.)
	Energy Resource	• Energy consumption within an organization for maintenance processes (fuel, electricity, heating, cooling, steam) through vehicles, equipment and tools owned or controlled by organization • Energy intensity (A): ratio between absolute energy consumption for maintenance processes and the organization-specific metric (*e.g. units of product of organization, production volume, size, #employees*) • Reduction of energy consumption as a direct result of reduction initiatives taken by maintenance processes (*e.g. conversion and retrofitting of equipment used for maintenance activities*) • Energy emitted *(e.g. heat, vibration*) by maintenance processes • Energy intensity (B): Ratio between energy used by maintenance processes and energy available for these processes or the organization • Number of initiatives implemented by maintenance process for energy-efficiency improvements (*e.g. initiatives on the used tools*) • Number of initiatives implemented by maintenance process for indirect energy-efficiency improvements (*e.g. initiatives on the equipment to be maintained)* • Ratio of the actual energy consumed by maintenance processes to the theoretical energy needed for the maintenance processes
	Land Resource	• Maintenance waste effects on land quality (*e.g. indicated by surface integrity, soil nutrients and contaminants, non-fertile land*)

Table A.21 – *Cube of knowledge: environmental indicators of maintenance system affected by BUD maintenance process (pt3)*

		MAINTENANCE SYSTEM – DIRECT IMPACT
	Sub-Category	**MAINTENANCE PROCESS: BUD - Maintenance budget of items**
ENVIRONMENTAL CATEGORY	***Materials Resource***	• Materials used for maintenance processes (*e.g. spare parts, documentation*) divided in renewable and non-renewable materials or with a breakdown on type of used materials (virgin, reused, recycled, remanufactured, repurposed) • Material intensity: ratio between the amount of materials needed for maintenance and the amount of materials used by maintenance • Quantity of auxiliary fluids used by maintenance processes (*e.g. cleaners, lubricants, oils, coolants*)
	Non-compliance with environmental laws and regulations	
	Supplier environmental assessment	
	Water Resource	• Volume of water withdrawn for maintenance processes with a breakdown by the sources (*e.g. lakes, rivers, ground water, rainwater*)

Table A.22 – *Cube of knowledge: social indicators of maintenance system affected by BUD maintenance process*

		MAINTENANCE SYSTEM – DIRECT IMPACT
	Sub-Category	**MAINTENANCE PROCESS: BUD - Maintenance budget of items**
SOCIAL CATEGORY	***Customers***	
	Employees	• Number of employees in maintenance processes per unit of product or sales or revenues • Maintenance employee health and safety including: -type of injury and injury rate (*e.g. through #maintenance accidents requiring first aid*); -occupational disease rate; -lost workday rate due to maintenance accidents or diseases; -absentee rate; -work related fatalities arising from maintenance injury or occupational disease • Number of safety measures adopted and safety/fail-safe equipment installed due to maintenance employee suggestions, and improvements in safety performance from these suggestions
	Non-compliance with laws and regulations in the social and economic area	• Significant fines and non-monetary sanctions for non-compliance of maintenance activities with laws and regulations in the social and economic area
	Supplier social assessment	

Table A.23 – *Cube of knowledge: economic indicators of maintenance system affected by IST maintenance process*

		MAINTENANCE SYSTEM – DIRECT IMPACT
	Sub-Category	**MAINTENANCE PROCESS: IST - Provide needed infrastructures**
ECONOMIC CATEGORY	***Economic Performance***	• Costs associated with EHS (Environment, Health, and Safety) compliance (*e.g. fines, liabilities, worker compensation, cost/depreciation of control equipment, remediation cost, labour cost*) of maintenance activities • Costs for acquisition of spare parts, materials, consumables • Costs of energy used by maintenance processes (*e.g. tools, means of transports, parts*) • Costs of maintenance employees • Costs for maintenance waste treatment • Ratio of actual labour hours to planned labour hours in performing a maintenance operation
	Investments	• Investments in development of infrastructure and services supported

Table A.24 – *Cube of knowledge: environmental indicators of maintenance system affected by IST maintenance process (pt1)*

		MAINTENANCE SYSTEM – DIRECT IMPACT
	Sub-Category	**MAINTENANCE PROCESS: IST - Provide needed infrastructures**
ENVIRONMENTAL CATEGORY	***Effluents and Wastes***	• Amount of wastes generated by maintenance processes (*e.g. replaced items, used tools, lubricants, oils, documentation*) specified by waste type and disposal method (*i.e. hazardous and non-hazardous, recyclable, reusable, remanufacturable, disposable*) • Amount of waste water discharged by maintenance processes specified by quality (*e.g. eco-toxic, hazardous, treated, non-treated, reused*) and destination • Amount of WEEE produced by maintenance processes • Maintenance waste effects on the surface integrity of surrounding buildings and places
	Emissions	• Direct GHG emissions: CO_2-eq due to electricity, heating, cooling and steam consumed by maintenance processes; transportation of materials, spare parts, and maintenance workers on the field. (*Gases included in the calculation are CO2, CH4, N2O, HFCs, PFCs, SF6, NF3, or all*). • Indirect GHG emissions: CO_2-eq due to purchased or acquired electricity, heating, cooling, and steam consumed by maintenance processes • GHG emissions intensity: ratio between absolute GHG emissions associated to maintenance processes and the organization-specific metric (*e.g. units of product of organization, production volume, size, #employees*) • Reduction of GHG emissions as a direct result of reduction initiatives taken by maintenance processes (*e.g. conversion and retrofitting of equipment used for maintenance activities*) • Ozone-depleting substances produced due to maintenance processes (*e.g. generated by air conditioners, solvents for cleaning, electronic equipment*) • Air emissions (such as NOX, SOX, POP (Persistent Organic Pollutants), VOC (Volatile Organic Compounds), HAP (Hazardous Air Pollutants), PM (Particulate Matter)) deriving from used chemicals, additives for lubricants, waste incineration, transportation and other, due to maintenance activities • Air quality within an organization and in its surrounding areas due to maintenance processes (smog, visibility, odour, GHG concentration, pollutant concentration, etc.)

Table A.25 – *Cube of knowledge: environmental indicators of maintenance system affected by IST maintenance process (pt2)*

		MAINTENANCE SYSTEM – DIRECT IMPACT
	Sub-Category	**MAINTENANCE PROCESS: IST - Provide needed infrastructures**
ENVIRONMENTAL CATEGORY	***Energy Resource***	• Energy consumption within an organization for maintenance processes (fuel, electricity, heating, cooling, steam) through vehicles, equipment and tools owned or controlled by organization • Energy intensity (A): ratio between absolute energy consumption for maintenance processes and the organization-specific metric (*e.g. units of product of organization, production volume, size, #employees*) • Reduction of energy consumption as a direct result of reduction initiatives taken by maintenance processes (*e.g. conversion and retrofitting of equipment used for maintenance activities*) • Energy emitted *(e.g. heat, vibration*) by maintenance processes • Energy intensity (B): Ratio between energy used by maintenance processes and energy available for these processes or the organization • Ratio of the actual energy consumed by maintenance processes to the theoretical energy needed for the maintenance processes
	Land Resource	• Land used by maintenance infrastructure, categorized by fertile and non-fertile areas • Maintenance waste effects on land quality (*e.g. indicated by surface integrity, soil nutrients and contaminants, non-fertile land*)
	Materials Resource	• Materials used for maintenance processes (*e.g. spare parts, documentation*) divided in renewable and non-renewable materials or with a breakdown on type of used materials (virgin, reused, recycled, remanufactured, repurposed) • Material intensity: ratio between the amount of materials needed for maintenance and the amount of materials used by maintenance • Quantity of auxiliary fluids used by maintenance processes (*e.g. cleaners, lubricants, oils, coolants*)
	Non-compliance with environmental laws and regulations	• Significant fines and non-monetary sanctions for non-compliance of maintenance processes with environmental laws and regulations
	Supplier environmental assessment	
	Water Resource	• Volume of water withdrawn for maintenance processes with a breakdown by the sources (*e.g. lakes, rivers, ground water, rainwater*)

Table A.26 – *Cube of knowledge: social indicators of maintenance system affected by IST maintenance process*

		MAINTENANCE SYSTEM – DIRECT IMPACT
	Sub-Category	**MAINTENANCE PROCESS: IST - Provide needed infrastructures**
SOCIAL CATEGORY	***Customers***	
	Employees	• Number of employees in maintenance processes per unit of product or sales or revenues • Ratio between number of maintenance employee suggestions in quality, social and EHS performance and number of maintenance employees • Maintenance employee health and safety including: -type of injury and injury rate (*e.g. through #maintenance accidents requiring first aid*); -occupational disease rate; -lost workday rate due to maintenance accidents or diseases; -absentee rate; -work related fatalities arising from maintenance injury or occupational disease • Number of safety measures adopted and safety/fail-safe equipment installed due to maintenance employee suggestions, and improvements in safety performance from these suggestions
	Non-compliance with laws and regulations in the social and economic area	• Significant fines and non-monetary sanctions for non-compliance of maintenance activities with laws and regulations in the social and economic area
	Supplier social assessment	

Table A.27 – *Cube of knowledge: economic indicators of maintenance system affected by RES maintenance process*

	Sub-Category	MAINTENANCE SYSTEM – DIRECT IMPACT MAINTENANCE PROCESS: RES – Provide internal human resources
ECONOMIC CATEGORY	*Economic Performance*	• Costs associated with EHS (Environment, Health, and Safety) compliance (*e.g. fines, liabilities, worker compensation, cost/depreciation of control equipment, remediation cost, labour cost*) of maintenance activities • Costs for acquisition of spare parts, materials, consumables • Costs of energy used by maintenance processes (*e.g. tools, means of transports, parts*) • Costs of maintenance employees • Costs for hiring new maintenance personnel • Ratio of actual labour hours to planned labour hours in performing a maintenance operation
	Investments	

Table A.28 – *Cube of knowledge: environmental indicators of maintenance system affected by RES maintenance process (pt1)*

	Sub-Category	MAINTENANCE SYSTEM – DIRECT IMPACT MAINTENANCE PROCESS: RES – Provide internal human resources
ENVIRONMENTAL CATEGORY	*Effluents and Wastes*	• Amount of wastes generated by maintenance processes (*e.g. replaced items, used tools, lubricants, oils, documentation*) specified by waste type and disposal method (*i.e. hazardous and non-hazardous, recyclable, reusable, remanufacturable, disposable*) • Amount of waste water discharged by maintenance processes specified by quality (*e.g. eco-toxic, hazardous, treated, non-treated, reused*) and destination • Amount of WEEE produced by maintenance processes • Maintenance waste effects on the surface integrity of surrounding buildings and places
	Emissions	• Direct GHG emissions: CO_2-eq due to electricity, heating, cooling and steam consumed by maintenance processes; transportation of materials, spare parts, and maintenance workers on the field. (*Gases included in the calculation are CO2, CH4, N2O, HFCs, PFCs, SF6, NF3, or all*). • Indirect GHG emissions: CO_2-eq due to purchased or acquired electricity, heating, cooling, and steam consumed by maintenance processes • GHG emissions intensity: ratio between absolute GHG emissions associated to maintenance processes and the organization-specific metric (*e.g. units of product of organization, production volume, size, #employees*) • Reduction of GHG emissions as a direct result of reduction initiatives taken by maintenance processes (*e.g. conversion and retrofitting of equipment used for maintenance activities*) • Ozone-depleting substances produced due to maintenance processes (*e.g. generated by air conditioners, solvents for cleaning, electronic equipment*) • Air emissions (such as NOX, SOX, POP (Persistent Organic Pollutants), VOC (Volatile Organic Compounds), HAP (Hazardous Air Pollutants), PM (Particulate Matter)) deriving from used chemicals, additives for lubricants, waste incineration, transportation and other, due to maintenance activities • Air quality within an organization and in its surrounding areas due to maintenance processes (smog, visibility, odour, GHG concentration, pollutant concentration, etc.)

Table A.29 – *Cube of knowledge: environmental indicators of maintenance system affected by RES maintenance process (pt2)*

		MAINTENANCE SYSTEM – DIRECT IMPACT
	Sub-Category	**MAINTENANCE PROCESS: RES – Provide internal human resources**
ENVIRONMENTAL CATEGORY	***Energy Resource***	• Energy consumption within an organization for maintenance processes (fuel, electricity, heating, cooling, steam) through vehicles, equipment and tools owned or controlled by organization • Energy intensity (A): ratio between absolute energy consumption for maintenance processes and the organization-specific metric (*e.g. units of product of organization, production volume, size, #employees*) • Reduction of energy consumption as a direct result of reduction initiatives taken by maintenance processes (*e.g. conversion and retrofitting of equipment used for maintenance activities*) • Energy emitted *(e.g. heat, vibration*) by maintenance processes • Energy intensity (B): Ratio between energy used by maintenance processes and energy available for these processes or the organization • Ratio of the actual energy consumed by maintenance processes to the theoretical energy needed for the maintenance processes
	Land Resource	• Maintenance waste effects on land quality (*e.g. indicated by surface integrity, soil nutrients and contaminants, non-fertile land*)
	Materials Resource	• Materials used for maintenance processes (*e.g. spare parts, documentation*) divided in renewable and non-renewable materials or with a breakdown on type of used materials (virgin, reused, recycled, remanufactured, repurposed) • Material intensity: ratio between the amount of materials needed for maintenance and the amount of materials used by maintenance • Quantity of auxiliary fluids used by maintenance processes (*e.g. cleaners, lubricants, oils, coolants*)
	Non-compliance with environmental laws and regulations	
	Supplier environmental assessment	
	Water Resource	• Volume of water withdrawn for maintenance processes with a breakdown by the sources (*e.g. lakes, rivers, ground water, rainwater*)

Table A.30 – *Cube of knowledge: social indicators of maintenance system affected by RES maintenance process*

		MAINTENANCE SYSTEM – DIRECT IMPACT
	Sub-Category	**MAINTENANCE PROCESS: RES – Provide internal human resources**
SOCIAL CATEGORY	***Customers***	
	Employees	• Number of employees in maintenance processes per unit of product or sales or revenues • New employee hires and employee turnover: number and rate of new maintenance employee hires during the reporting period, by age group, gender and region; number and rate of maintenance employee turnover during the reporting period, by age group, gender and region • Ratio between number of maintenance employee suggestions in quality, social and EHS performance and number of maintenance employees • Revitalization of maintenance employee suggestions for improvement and specific effort periods (*e.g. one month, one week a month*) • Average hours of training per year per maintenance employees: ratio between #training hours and #maintenance employees • %maintenance employees trained in basic sustainability concepts and/or current sustainability initiatives • Skill management programs provided by maintenance processes • Type and scope of training programs and assistance provided by maintenance processes for upgrading employee skills • %maintenance employees who report complete job satisfaction *(e.g. through use of questionnaire, surveys*) • %maintenance employees by gender who received a regular performance and career development review • Number or % maintenance employees empowered with the knowledge to make safer choices for themselves and coach their peers to do the same • Maintenance employee health and safety including: -type of injury and injury rate (*e.g. through #maintenance accidents requiring first aid*); -occupational disease rate; -lost workday rate due to maintenance accidents or diseases; -absentee rate; -work related fatalities arising from maintenance injury or occupational disease • Number of safety measures adopted and safety/fail-safe equipment installed due to maintenance employee suggestions, and improvements in safety performance from these suggestions
	Non-compliance with laws and regulations in the social and economic area	• Significant fines and non-monetary sanctions for non-compliance of maintenance activities with laws and regulations in the social and economic area
	Supplier social assessment	

Table A.31 – *Cube of knowledge: economic indicators of maintenance system affected by SPP maintenance process*

	Sub-Category	MAINTENANCE SYSTEM – DIRECT IMPACT MAINTENANCE PROCESS: SPP – Deliver spare parts
ECONOMIC CATEGORY	***Economic Performance***	• Costs associated with EHS (Environment, Health, and Safety) compliance (*e.g. fines, liabilities, worker compensation, cost/depreciation of control equipment, remediation cost, labour cost*) of maintenance activities • Costs for acquisition of spare parts, materials, consumables • Costs of energy used by maintenance processes (*e.g. tools, means of transports, parts*) • Costs of maintenance employees • Costs of storage for spare parts and tools used in maintenance activities • Costs to recycle spare parts or WEEE (Waste Electric and Electronic Equipment) • Ratio of actual labour hours to planned labour hours in performing a maintenance operation
	Investments	

Table A.32 – *Cube of knowledge: environmental indicators of maintenance system affected by SPP maintenance process (pt1)*

	Sub-Category	MAINTENANCE SYSTEM – DIRECT IMPACT MAINTENANCE PROCESS: SPP – Deliver spare parts
ENVIRONMENTAL CATEGORY	***Effluents and Wastes***	• Amount of wastes generated by maintenance processes (*e.g. replaced items, used tools, lubricants, oils, documentation*) specified by waste type and disposal method (*i.e. hazardous and non-hazardous, recyclable, reusable, remanufacturable, disposable*) • Amount of waste water discharged by maintenance processes specified by quality (*e.g. eco-toxic, hazardous, treated, non-treated, reused*) and destination • Volume of recorded significant spills (*i.e. accidental release of hazardous substances that can affect human health, land, vegetation, water bodies, and ground water*) derived by maintenance processes • Amount of WEEE produced by maintenance processes • Maintenance waste effects on the surface integrity of surrounding buildings and places
	Emissions	• Direct GHG emissions: CO_2-eq due to electricity, heating, cooling and steam consumed by maintenance processes; transportation of materials, spare parts, and maintenance workers on the field. (*Gases included in the calculation are CO2, CH4, N2O, HFCs, PFCs, SF6, NF3, or all*). • Indirect GHG emissions: CO_2-eq due to purchased or acquired electricity, heating, cooling, and steam consumed by maintenance processes • GHG emissions intensity: ratio between absolute GHG emissions associated to maintenance processes and the organization-specific metric (*e.g. units of product of organization, production volume, size, #employees*) • Reduction of GHG emissions as a direct result of reduction initiatives taken by maintenance processes (*e.g. conversion and retrofitting of equipment used for maintenance activities*) • Ozone-depleting substances produced due to maintenance processes (*e.g. generated by air conditioners, solvents for cleaning, electronic equipment*) • Air emissions (such as NOX, SOX, POP (Persistent Organic Pollutants), VOC (Volatile Organic Compounds), HAP (Hazardous Air Pollutants), PM (Particulate Matter)) deriving from used chemicals, additives for lubricants, waste incineration, transportation and other, due to maintenance activities • Air quality within an organization and in its surrounding areas due to maintenance processes (smog, visibility, odour, GHG concentration, pollutant concentration, etc.)

Table A.33 – *Cube of knowledge: environmental indicators of maintenance system affected by SPP maintenance process (pt2)*

		MAINTENANCE SYSTEM – DIRECT IMPACT
	Sub-Category	**MAINTENANCE PROCESS: SPP – Deliver spare parts**
ENVIRONMENTAL CATEGORY	***Energy Resource***	• Energy consumption within an organization for maintenance processes (fuel, electricity, heating, cooling, steam) through vehicles, equipment and tools owned or controlled by organization • Energy consumption outside the organization for maintenance processes (*f.e transportation and distribution of spare part suppliers*) • Energy intensity (A): ratio between absolute energy consumption for maintenance processes and the organization-specific metric (*e.g. units of product of organization, production volume, size, #employees*) • Reduction of energy consumption as a direct result of reduction initiatives taken by maintenance processes (*e.g. conversion and retrofitting of equipment used for maintenance activities*) • Energy emitted *(e.g. heat, vibration*) by maintenance processes • Energy intensity (B): Ratio between energy used by maintenance processes and energy available for these processes or the organization • Ratio of the actual energy consumed by maintenance processes to the theoretical energy needed for the maintenance processes
	Land Resource	• Maintenance waste effects on land quality (*e.g. indicated by surface integrity, soil nutrients and contaminants, non-fertile land*)
	Materials Resource	• Materials used for maintenance processes (*e.g. spare parts, documentation*) divided in renewable and non-renewable materials or with a breakdown on type of used materials (virgin, reused, recycled, remanufactured, repurposed) • Quantity of PBT (Persistent, Bioaccumulative and Toxic) chemicals used due to maintenance processes • %recycled input materials: ratio between total input recycled materials and total used materials for maintenance processes • Material intensity: ratio between the amount of materials needed for maintenance and the amount of materials used by maintenance • Quantity of auxiliary fluids used by maintenance processes (*e.g. cleaners, lubricants, oils, coolants*)
	Non-compliance with environmental laws and regulations	• Significant fines and non-monetary sanctions for non-compliance of maintenance processes with environmental laws and regulations
	Supplier environmental assessment	• %new suppliers that were screened using environmental criteria
	Water Resource	• Volume of water withdrawn for maintenance processes with a breakdown by the sources (*e.g. lakes, rivers, ground water, rainwater*)

Table A.34 – *Cube of knowledge: social indicators of maintenance system affected by SPP maintenance process*

		MAINTENANCE SYSTEM – DIRECT IMPACT
	Sub-Category	**MAINTENANCE PROCESS: SPP – Deliver spare parts**
SOCIAL CATEGORY	***Customers***	
	Employees	• Number of employees in maintenance processes per unit of product or sales or revenues • Ratio between number of maintenance employee suggestions in quality, social and EHS performance and number of maintenance employees • Maintenance employee health and safety including: -type of injury and injury rate (*e.g. through #maintenance accidents requiring first aid*); -occupational disease rate; -lost workday rate due to maintenance accidents or diseases; -absentee rate; -work related fatalities arising from maintenance injury or occupational disease • Number of safety measures adopted and safety/fail-safe equipment installed due to maintenance employee suggestions, and improvements in safety performance from these suggestions
	Non-compliance with laws and regulations in the social and economic area	• Significant fines and non-monetary sanctions for non-compliance of maintenance activities with laws and regulations in the social and economic area
	Supplier social assessment	• %suppliers that were screened with social criteria

Table A.35 – *Cube of knowledge: economic indicators of maintenance system affected by TOL maintenance process*

		MAINTENANCE SYSTEM – DIRECT IMPACT
	Sub-Category	**MAINTENANCE PROCESS: TOL – Deliver tools, support equipment and information system**
ECONOMIC CATEGORY	***Economic Performance***	• Costs associated with EHS (Environment, Health, and Safety) compliance (*e.g. fines, liabilities, worker compensation, cost/depreciation of control equipment, remediation cost, labour cost*) of maintenance activities • Costs for acquisition of spare parts, materials, consumables • Costs of energy used by maintenance processes (*e.g. tools, means of transports, parts*) • Costs for purchase of maintenance tools • Costs of maintenance employees • Costs of storage for spare parts and tools used in maintenance activities • Ratio of actual labour hours to planned labour hours in performing a maintenance operation
	Investments	

Table A.36 – *Cube of knowledge: environmental indicators of maintenance system affected by TOL maintenance process (pt1)*

		MAINTENANCE SYSTEM – DIRECT IMPACT
	Sub-Category	**MAINTENANCE PROCESS: TOL – Deliver tools, support equipment and information system**
ENVIRONMENTAL CATEGORY	***Effluents and Wastes***	• Amount of wastes generated by maintenance processes (*e.g. replaced items, used tools, lubricants, oils, documentation*) specified by waste type and disposal method (*i.e. hazardous and non-hazardous, recyclable, reusable, remanufacturable, disposable*) • Amount of waste water discharged by maintenance processes specified by quality (*e.g. eco-toxic, hazardous, treated, non-treated, reused*) and destination • Amount of WEEE produced by maintenance processes • Maintenance waste effects on the surface integrity of surrounding buildings and places
	Emissions	• Direct GHG emissions: CO_2-eq due to electricity, heating, cooling and steam consumed by maintenance processes; transportation of materials, spare parts, and maintenance workers on the field. (*Gases included in the calculation are CO2, CH4, N2O, HFCs, PFCs, SF6, NF3, or all*). • Indirect GHG emissions: CO_2-eq due to purchased or acquired electricity, heating, cooling, and steam consumed by maintenance processes • GHG emissions intensity: ratio between absolute GHG emissions associated to maintenance processes and the organization-specific metric (*e.g. units of product of organization, production volume, size, #employees*) • Reduction of GHG emissions as a direct result of reduction initiatives taken by maintenance processes (*e.g. conversion and retrofitting of equipment used for maintenance activities*) • Ozone-depleting substances produced due to maintenance processes (*e.g. generated by air conditioners, solvents for cleaning, electronic equipment*) • Air emissions (such as NOX, SOX, POP (Persistent Organic Pollutants), VOC (Volatile Organic Compounds), HAP (Hazardous Air Pollutants), PM (Particulate Matter)) deriving from used chemicals, additives for lubricants, waste incineration, transportation and other, due to maintenance activities • Air quality within an organization and in its surrounding areas due to maintenance processes (smog, visibility, odour, GHG concentration, pollutant concentration, etc.)

Table A.37 – *Cube of knowledge: environmental indicators of maintenance system affected by TOL maintenance process (pt2)*

	Sub-Category	MAINTENANCE SYSTEM – DIRECT IMPACT MAINTENANCE PROCESS: TOL – Deliver tools, support equipment and information system
ENVIRONMENTAL CATEGORY	***Energy Resource***	• Energy consumption within an organization for maintenance processes (fuel, electricity, heating, cooling, steam) through vehicles, equipment and tools owned or controlled by organization • Energy intensity (A): ratio between absolute energy consumption for maintenance processes and the organization-specific metric (*e.g. units of product of organization, production volume, size, #employees*) • Reduction of energy consumption as a direct result of reduction initiatives taken by maintenance processes (*e.g. conversion and retrofitting of equipment used for maintenance activities*) • Energy emitted *(e.g. heat, vibration*) by maintenance processes • Energy intensity (B): Ratio between energy used by maintenance processes and energy available for these processes or the organization • Ratio of the actual energy consumed by maintenance processes to the theoretical energy needed for the maintenance processes
	Land Resource	• Maintenance waste effects on land quality (*e.g. indicated by surface integrity, soil nutrients and contaminants, non-fertile land*)
	Materials Resource	• Materials used for maintenance processes (*e.g. spare parts, documentation*) divided in renewable and non-renewable materials or with a breakdown on type of used materials (virgin, reused, recycled, remanufactured, repurposed) • %recycled input materials: ratio between total input recycled materials and total used materials for maintenance processes • Material intensity: ratio between the amount of materials needed for maintenance and the amount of materials used by maintenance • Quantity of auxiliary fluids used by maintenance processes (*e.g. cleaners, lubricants, oils, coolants*)
	Non-compliance with environmental laws and regulations	• Significant fines and non-monetary sanctions for non-compliance of maintenance processes with environmental laws and regulations
	Supplier environmental assessment	
	Water Resource	• Volume of water withdrawn for maintenance processes with a breakdown by the sources (*e.g. lakes, rivers, ground water, rainwater*)

Table A.38 – *Cube of knowledge: social indicators of maintenance system affected by TOL maintenance process*

		MAINTENANCE SYSTEM – DIRECT IMPACT
	Sub-Category	**MAINTENANCE PROCESS: TOL – Deliver tools, support equipment and information system**
SOCIAL CATEGORY	***Customers***	
SOCIAL CATEGORY	***Employees***	• Number of employees in maintenance processes per unit of product or sales or revenues • Ratio between number of maintenance employee suggestions in quality, social and EHS performance and number of maintenance employees • Maintenance employee health and safety including: -type of injury and injury rate (*e.g. through #maintenance accidents requiring first aid*); -occupational disease rate; -lost workday rate due to maintenance accidents or diseases; -absentee rate; -work related fatalities arising from maintenance injury or occupational disease • Personal protective equipment and safety equipment provided by maintenance processes • Number of safety measures adopted and safety/fail-safe equipment installed due to maintenance employee suggestions, and improvements in safety performance from these suggestions
SOCIAL CATEGORY	***Non-compliance with laws and regulations in the social and economic area***	• Significant fines and non-monetary sanctions for non-compliance of maintenance activities with laws and regulations in the social and economic area
SOCIAL CATEGORY	***Supplier social assessment***	

Table A.39 – *Cube of knowledge: economic indicators of maintenance system affected by all maintenance processes*

		MAINTENANCE SYSTEM – DIRECT IMPACT
	Sub-Category	**MAINTENANCE MANAGEMENT, REALISATION, SUPPORT PROCESSES**
ECONOMIC CATEGORY	***Economic Performance***	• Costs associated with EHS (Environment, Health, and Safety) compliance (*e.g. fines, liabilities, worker compensation, cost/depreciation of control equipment, remediation cost, labour cost*) of maintenance activities • Costs for acquisition of spare parts, materials, consumables • Costs of energy used by maintenance processes (*e.g. tools, means of transports, parts*) • Costs for purchase of maintenance tools • Costs of maintenance employees • Costs for hiring new maintenance personnel • Costs for maintenance waste treatment • Costs of storage for spare parts and tools used in maintenance activities • Costs for managing maintenance employee responsibilities in reporting or assessing risks • Costs to recycle spare parts or WEEE (Waste Electric and Electronic Equipment) • Ratio of actual labour hours to planned labour hours in performing a maintenance operation
	Investments	• Investments in energy efficiency instruments and initiatives taken by maintenance processes • Investments and expenditures in scientific research and experimental development (R&D), e.g. for new innovative technologies, taken by maintenance processes • Investments in development of infrastructure and services supported

Table A.40 – *Cube of knowledge: environmental indicators of maintenance system affected by all maintenance processes (pt1)*

		MAINTENANCE SYSTEM – DIRECT IMPACT
	Sub-Category	**MAINTENANCE MANAGEMENT, REALISATION, SUPPORT PROCESSES**
ENVIRONMENTAL CATEGORY	***Effluents and Wastes***	• Amount of wastes generated by maintenance processes (*e.g. replaced items, used tools, lubricants, oils, documentation*) specified by waste type and disposal method (*i.e. hazardous and non-hazardous, recyclable, reusable, remanufacturable, disposable*) • Amount of waste water discharged by maintenance processes specified by quality (*e.g. eco-toxic, hazardous, treated, non-treated, reused*) and destination • Volume of recorded significant spills (*i.e. accidental release of hazardous substances that can affect human health, land, vegetation, water bodies, and ground water*) derived by maintenance processes • Transport of hazardous waste generated by maintenance activities • Amount of WEEE produced by maintenance processes • Maintenance waste effects on the surface integrity of surrounding buildings and places

Table A.41 – *Cube of knowledge: environmental indicators of maintenance system affected by all maintenance processes (pt2)*

		MAINTENANCE SYSTEM – DIRECT IMPACT
	Sub-Category	**MAINTENANCE MANAGEMENT, REALISATION, SUPPORT PROCESSES**
ENVIRONMENTAL CATEGORY	***Emissions***	• Direct GHG emissions: CO_2-eq due to electricity, heating, cooling and steam consumed by maintenance processes; transportation of materials, spare parts, and maintenance workers on the field. (*Gases included in the calculation are CO2, CH4, N2O, HFCs, PFCs, SF6, NF3, or all*). • Indirect GHG emissions: CO_2-eq due to purchased or acquired electricity, heating, cooling, and steam consumed by maintenance processes • GHG emissions intensity: ratio between absolute GHG emissions associated to maintenance processes and the organization-specific metric (*e.g. units of product of organization, production volume, size, #employees*) • Reduction of GHG emissions as a direct result of reduction initiatives taken by maintenance processes (*e.g. conversion and retrofitting of equipment used for maintenance activities*) • Ozone-depleting substances produced due to maintenance processes (*e.g. generated by air conditioners, solvents for cleaning, electronic equipment*) • Air emissions (such as NOX, SOX, POP (Persistent Organic Pollutants), VOC (Volatile Organic Compounds), HAP (Hazardous Air Pollutants), PM (Particulate Matter)) deriving from used chemicals, additives for lubricants, waste incineration, transportation and other, due to maintenance activities • Noise emissions for maintenance processes • Air quality within an organization and in its surrounding areas due to maintenance processes (smog, visibility, odour, GHG concentration, pollutant concentration, etc.)
	Energy Resource	• Energy consumption within an organization for maintenance processes (fuel, electricity, heating, cooling, steam) through vehicles, equipment and tools owned or controlled by organization • Energy consumption outside the organization for maintenance processes (*e.g. transportation and distribution of spare part suppliers*) • Energy intensity (A): ratio between absolute energy consumption for maintenance processes and the organization-specific metric (*e.g. units of product of organization, production volume, size, #employees*) • Reduction of energy consumption as a direct result of reduction initiatives taken by maintenance processes (*e.g. conversion and retrofitting of equipment used for maintenance activities*) • Energy emitted *(e.g. heat, vibration*) by maintenance processes • Energy intensity (B): Ratio between energy used by maintenance processes and energy available for these processes or the organization • Number of initiatives implemented by maintenance process for energy-efficiency improvements (*e.g. initiatives on the used tools*) • Number of initiatives implemented by maintenance process for indirect energy-efficiency improvements (*e.g. initiatives on the equipment to be maintained)* • Ratio of the actual energy consumed by maintenance processes to the theoretical energy needed for the maintenance processes
	Land Resource	• Land used by maintenance infrastructure, categorized by fertile and non-fertile areas • Maintenance waste effects on land quality (*e.g. indicated by surface integrity, soil nutrients and contaminants, non-fertile land*)

Table A.42 – *Cube of knowledge: environmental indicators of maintenance system affected by all maintenance processes (pt3)*

		MAINTENANCE SYSTEM – DIRECT IMPACT
	Sub-Category	**MAINTENANCE MANAGEMENT, REALISATION, SUPPORT PROCESSES**
ENVIRONMENTAL CATEGORY	***Materials Resource***	• Materials used for maintenance processes (*e.g. spare parts, documentation*) divided in renewable and non-renewable materials or with a breakdown on type of used materials (virgin, reused, recycled, remanufactured, repurposed) • Quantity of PBT (Persistent, Bioaccumulative and Toxic) chemicals used due to maintenance processes • %recycled input materials: ratio between total input recycled materials and total used materials for maintenance processes • Material intensity: ratio between the amount of materials needed for maintenance and the amount of materials used by maintenance • Quantity of auxiliary fluids used by maintenance processes (*e.g. cleaners, lubricants, oils, coolants*)
	Non-compliance with environmental laws and regulations	• Significant fines and non-monetary sanctions for non-compliance of maintenance processes with environmental laws and regulations
	Supplier environmental assessment	• %new suppliers that were screened using environmental criteria
	Water Resource	• Volume of water withdrawn for maintenance processes with a breakdown by the sources (*e.g. lakes, rivers, ground water, rainwater*)

Table A.43 – *Cube of knowledge: social indicators of maintenance system affected by all maintenance processes (pt1)*

		MAINTENANCE SYSTEM – DIRECT IMPACT
	Sub-Category	**MAINTENANCE MANAGEMENT, REALISATION, SUPPORT PROCESSES**
SOCIAL CATEGORY	***Non-compliance with laws and regulations in the social and economic area***	• Significant fines and non-monetary sanctions for non-compliance of maintenance activities with laws and regulations in the social and economic area
	Supplier social assessment	• %suppliers that were screened with social criteria

Table A.44 – *Cube of knowledge: social indicators of maintenance system affected by all maintenance processes (pt2)*

		MAINTENANCE SYSTEM – DIRECT IMPACT
	Sub-Category	**MAINTENANCE MANAGEMENT, REALISATION, SUPPORT PROCESSES**
SOCIAL CATEGORY	***Customers***	
	Employees	• Number of employees in maintenance processes per unit of product or sales or revenues • New employee hires and employee turnover: number and rate of new maintenance employee hires during the reporting period, by age group, gender and region; number and rate of maintenance employee turnover during the reporting period, by age group, gender and region • Ratio between number of maintenance employee suggestions in quality, social and EHS performance and number of maintenance employees • Revitalization of maintenance employee suggestions for improvement and specific effort periods (*e.g. one month, one week a month*) • Average hours of training per year per maintenance employees: ratio between #training hours and #maintenance employees • %maintenance employees trained in basic sustainability concepts and/or current sustainability initiatives • Skill management programs provided by maintenance processes • Type and scope of training programs and assistance provided by maintenance processes for upgrading employee skills • %maintenance employees who report complete job satisfaction *(e.g. through use of questionnaire, surveys*) • %maintenance employees by gender who received a regular performance and career development review • Number or % maintenance employees empowered with the knowledge to make safer choices for themselves and coach their peers to do the same • Maintenance employee health and safety including: -type of injury and injury rate (*e.g. through #maintenance accidents requiring first aid*); -occupational disease rate; -lost workday rate due to maintenance accidents or diseases; -absentee rate; -work related fatalities arising from maintenance injury or occupational disease • Maintenance employees with high incidence or high risk of diseases related to their occupation • Diffusion of work-related illness: increase/decrease in number of maintenance employees affected by work-related illness • Personal protective equipment and safety equipment provided by maintenance processes • Number of safety measures adopted by maintenance processes, safety/fail-safe equipment installed, and improvements in safety performance from these measures • Number of safety measures adopted and safety/fail-safe equipment installed due to maintenance employee suggestions, and improvements in safety performance from these suggestions • Education, training, counselling, prevention, and risk-control programs in place to assist maintenance workforce members and their families regarding serious diseases • Education, training, counselling, prevention, and employee empowerment to limit the risk of work place injuries

Table A.45 – *Cube of knowledge: economic indicators of target system indirectly affected by all maintenance processes*

	Sub-Category	MAINTENANCE MANAGEMENT, REALISATION, SUPPORT PROCESSES TARGET SYSTEM – INDIRECT IMPACT
ECONOMIC CATEGORY	***Economic Performance***	• Costs associated with EHS (Environment, Health, and Safety) compliance (*e.g. fines, liabilities, worker compensation, cost/depreciation of control equipment, remediation cost, labour cost*) of production activities • Costs for acquisition of materials for production process • Costs of energy used by production process • Costs of employees of the production process • Costs for waste treatment of production process • Ratio of actual labour hours of production to planned labour hours of production
ECONOMIC CATEGORY	***Investments***	

Table A.46 – *Cube of knowledge: environmental indicators of target system indirectly affected by all maintenance processes (pt1)*

	Sub-Category	MAINTENANCE MANAGEMENT, REALISATION, SUPPORT PROCESSES TARGET SYSTEM – INDIRECT IMPACT
ENVIRONMENTAL ACTEGORY	***Effluents and Wastes***	• Amount of wastes generated by production process specified by waste type and disposal method (*i.e. hazardous and non-hazardous, recyclable, reusable, remanufacturable, disposable*) • Volume of recorded significant spills (*i.e. accidental release of hazardous substances that can affect human health, land, vegetation, water bodies, and ground water*) from machines of production process • Transport of hazardous waste generated by production process • Amount of WEEE produced by production process • Production waste effects on the surface integrity of surrounding buildings and places
ENVIRONMENTAL ACTEGORY	***Emissions***	• Direct GHGs emissions: CO_2-equivalent due to electricity, heating, cooling and steam consumed by production process; transportation of materials, products, workers. (*Gases included in the calculation are CO2, CH4, N2O, HFCs, PFCs, SF6, NF3, or all*). • Indirect GHGs emissions: CO_2-eq due to purchased or acquired electricity, heating, cooling, and steam consumed by production process • GHG emissions intensity: ratio between absolute GHG emissions associated to production process and the organization-specific metric (*e.g. units of product of organization, production volume, size, #employees*) • Reduction of GHG emissions of production process as a direct result of reduction initiatives taken by an organization (*e.g. process redesign, conversion and retrofitting of equipment, fuel switching*) • Air emissions (such as NOX, SOX, POP (Persistent Organic Pollutants), VOC (Volatile Organic Compounds), HAP (Hazardous Air Pollutants), PM (Particulate Matter)) deriving from production process • Noise emissions for production process • Air quality within an organization and in its surrounding areas due to production process (smog, visibility, odour, GHG concentration, pollutant concentration, etc.)

Table A.47 – *Cube of knowledge: environmental indicators of target system indirectly affected by all maintenance processes (pt2)*

		MAINTENANCE MANAGEMENT, REALISATION, SUPPORT PROCESSES
	Sub-Category	**TARGET SYSTEM – INDIRECT IMPACT**
ENVIRONMENTAL ACTEGORY	***Energy Resource***	• Energy consumption of production process • Energy intensity: ratio between absolute energy consumption for production process and the organization-specific metric (*e.g. units of product of organization, production volume, size, #employees*) • Reduction of energy consumption of production process as a direct result of reduction initiatives taken by an organization (*e.g. process redesign, conversion and retrofitting of equipment*) • Energy emitted *(e.g. heat, vibration*) by production process • Energy intensity (B): Ratio between energy used by production process and energy available for this process or the organization • Ratio of the actual energy consumed by production process to the theoretical energy needed for the production process
	Land Resource	• Production waste effects on land quality (*e.g. indicated by surface integrity, soil nutrients and contaminants, non-fertile land*)
	Materials Resource	• Materials used for production process (*e.g. raw materials, semi-manufactured goods or parts, auxiliary materials*) divided in renewable and non-renewable materials or with a breakdown on type of used materials (virgin, reused, recycled, remanufactured, repurposed) • Quantity of PBT (Persistent, Bioaccumulative and Toxic) chemicals used for production processes • Material intensity: ratio between the amount of materials needed for production process and the amount of materials used by production process
	Non-compliance with environmental laws and regulations	• Significant fines and non-monetary sanctions for production process non-compliant with environmental laws and regulations
	Supplier environmental assessment	
	Water Resource	• Volume of water withdrawn for production process with a breakdown by the sources (*e.g. lakes, rivers, ground water, rainwater*)

Table A.48 – *Cube of knowledge: social indicators of target system indirectly affected by all maintenance processes*

		MAINTENANCE MANAGEMENT, REALISATION, SUPPORT PROCESSES
	Sub-Category	**TARGET SYSTEM – INDIRECT IMPACT**
SOCIAL CATEGORY	***Customers***	
	Employees	• Ratio between number of production employee suggestions in quality, social and EHS performance and number of production employees • %production employees who report complete job satisfaction *(e.g. through use of questionnaire, surveys*) • Production employee health and safety including: -type of injury and injury rate (*e.g. through #accidents requiring first aid*); -occupational disease rate; -lost workday rate due to production accidents or diseases; -absentee rate; -work related fatalities arising from injury or occupational disease on production system • Production employees with high incidence or high risk of diseases related to their occupation • Number of safety measures adopted and safety/fail-safe equipment installed due to production employee suggestions, and improvements in safety performance from these suggestions
	Non-compliance with laws and regulations in the social and economic area	• Significant fines and non-monetary sanctions for production process non-compliant with social-economic laws and regulations
	Supplier social assessment	

Table A.49 – *Cube of knowledge: economic indicators of target system output indirectly affected by all maintenance processes*

		MAINTENANCE MANAGEMENT, REALISATION, SUPPORT PROCESSES
	Sub-Category	**TARGET SYSTEM OUTPUT – INDIRECT IMPACT**
ECONOMIC CATEGORY	***Economic Performance***	• Costs for acquisition of materials necessary to achieve the final product • Costs for packaging of manufactured product • Costs for transportation of manufactured product to the customer • Cost for energy used during the use-phase of a product
	Investments	

Table A.50 – *Cube of knowledge: environmental indicators of target system output indirectly affected by all maintenance processes*

		MAINTENANCE MANAGEMENT, REALISATION, SUPPORT PROCESSES
	Sub-Category	**TARGET SYSTEM OUTPUT – INDIRECT IMPACT**
ENVIRONMENTAL CATEGORY	***Effluents and Wastes***	• Amount of waste derived by non-compliant or defective products
	Emissions	• Direct GHG emissions: CO_2-eq due to electricity, heating, cooling and steam consumed by the use of the manufactured product (*Gases included in the calculation are CO2, CH4, N2O, HFCs, PFCs, SF6, NF3, or all*). • Ozone-depleting substances produced by the use of manufactured product • Air emissions (such as NOX, SOX, POP (Persistent Organic Pollutants), VOC (Volatile Organic Compounds), HAP (Hazardous Air Pollutants), PM (Particulate Matter)) deriving from the use of the manufactured product • Air quality due to the use of the manufactured product (smog, visibility, odour, GHG concentration, pollutant concentration, etc.)
	Energy Resource	• Energy consumption associated with use of sold product, end-of-life treatment of sold products • Energy emitted *(e.g. heat, vibration*) by sold products • Ratio of the actual energy consumed by manufactured products to the theoretical energy needed for the manufactured product
	Land Resource	
	Materials Resource	• Materials used for manufactured and sold products (*e.g. raw materials, materials for packaging*) divided in renewable and non-renewable materials or with a breakdown on type of used materials (virgin, reused, recycled, remanufactured, repurposed) • Material intensity: ratio between the amount of materials needed for a manufactured product and the amount of materials used for the product
	Non-compliance with environmental laws and regulations	• Significant fines and non-monetary sanctions for provision of manufactured products non-compliant with environmental laws and regulations
	Supplier environmental assessment	
	Water Resource	

Table A.51 – *Cube of knowledge: social indicators of target system indirectly affected by all maintenance processes*

		MAINTENANCE MANAGEMENT, REALISATION, SUPPORT PROCESSES
	Sub-Category	**TARGET SYSTEM OUTPUT – INDIRECT IMPACT**
SOCIAL CATEGORY	***Customers***	• Number of incidents of non-compliance with regulations and/or voluntary codes concerning health and safety impacts of manufactured products • Investments or number of practices (*e.g. surveys*) to assess customer satisfaction • Number of customer complaints per year concerning a manufactured product • Product quality assurance and management: incidents of product recalls and customer complaints, and resolutions met from these incidents
	Employees	
	Non-compliance with laws and regulations in the social and economic area	• Significant fines and non-monetary sanctions for provision of manufactured products non-compliant with social-economic laws and regulations
	Supplier social assessment	

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