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A Maintenance Maturity and Sustainability Assessment Model for Manufacturing Systems

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Abstract
Maintenance is a key manufacturing function that contributes to a company's productivity, profitability and sustainability. Unfortunately, many aspects of the contribution of maintenance to sustainability in manufacturing remain unexplored, and many enterprises are not yet ready to assess the maintenance impacts on their sustainability. Maturity models are useful tools for assessing maintenance practices; however, no maintenance maturity model that allows the evaluation of the contribution of maintenance to sustainable performance was found in literature. This paper proposes a model for assessing the maturity and sustainability of maintenance processes. The model outputs are: a measure of the maintenance and sustainability maturity level; recommendations for improvement to undertake to enhance maintenance maturity and, thus, meet sustainability standards. The model was applied in three manufacturing enterprises: the calculation of their maintenance maturity and sustainability indices made the maintenance stakeholders more aware of the need to implement effective strategies for more sustainable maintenance performance.

Keywords
Maintenance, Sustainability, Maintenance impacts, Manufacturing systems, Maintenance performance measurement.

Introduction

The maintenance function is increasingly being recognised both in the scientific and normative worlds as a key process that can effectively contribute to the sustainable development of manufacturing companies if it is properly managed (Franciosi et al., 2021; Iung and Levrat, 2014; Jasiulewicz–Kaczmarek et al., 2021). Conversely, maintenance can have several significant negative impacts on the economic, environmental and social performance of manufacturing systems if it is not well-managed. These are because maintenance affects production volume and costs, asset performance, equipment availability, final product quality, people's health and safety, and the consumption of resources, such as energy and materials (Franciosi et al., 2018; Okoh and Haugen, 2014). To reduce and control such negative impacts, maintenance processes must be properly assessed and managed.

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The European Standard EN 13306 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'. Therefore, maintenance enables manufacturing organisations to keep their production systems efficient and their products at the required quality, with a consequently large potential to achieve sustainable manufacturing, thanks to its impact on several company's processes. Indeed, maintenance with a sustainable perspective can also be seen, according to Franciosi, Voisin et al. (2020), as:

... a set of interconnected processes that, on the one hand, has to sustain assets/equipment during their operation in order to guarantee compliance of the production process, of the manufactured products and to reduce their industrial impacts on the economy, society, and the surrounding environment; and, on the other hand, has to be a sustainable business function itself in order to limit its own flows and impacts generated during maintenance activities.

In this frame, advanced and best maintenance practices that contribute to sustainable business strategies need to be given a more central role in future research and practice (Holgado et al., 2020). However, only in the last few years has the role of maintenance as a contributor to sustainable operations attracted more attention in the research and practice fields.

Some recent studies showed empirical evidence of the impacts of maintenance practices on asset sustainability in manufacturing systems (Holgado et al., 2020; Ghaleb & Taghipour, 2022a). They illustrated the positive effect of maintenance on: the reduction of costs (e.g., maintenance costs, resource usage costs, production costs); the improvement of assets' technical performance (like availability, reliability, productivity, OEE, downtime); the reduction of social issues (as accidents and incidents); the environmental aspects (e.g., reduction of noise, energy and material consumption). Jasiulewicz-Kaczmarek et al. (2020) and Jasiulewicz-Kaczmarek & Gola (2019) underlined the urgence to consider sustainability goals in the conventional maintenance processes and discussed the opportunities of improvement of maintenance processes in the three sustainable dimensions, also thanks to data-driven maintenance approaches and the technologies 4.0, as well as the potential benefits that can be achieved in each dimension. Other recent studies focused on the assessment of maintenance practices from the technical, economic, environmental and social points of view and proposed several factors, indicators and methods to this aim (e.g., Franciosi, Di Pasquale et al., 2020; Franciosi, Voisin et al., 2020; Ghaleb & Taghipour, 2022b; Jasiulewicz-Kaczmarek, 2018; Jasiulewicz-Kaczmarek & Żywica, 2018; Pires et al., 2016; Sari et al., 2015). The standard EN15341:2019 on maintenance key performance indicators also proposed enhancements of the conventional technical and economic factors and indicators of maintenance performance.

Defining indicators of maintenance impacts on the three dimensions of sustainability (i.e., economic, environmental and social) is not only difficult but also requires much data. Most companies are still unaware of the large amount of direct and indirect impacts of maintenance on sustainability; in other words, they miss the proper level of maintenance maturity or readiness to assess such impacts.

In this complex context, maintenance maturity models are useful tools. Maturity models were generally designed to assess the maturity (i.e., the capability and level of sophistication) of a selected domain based on a more or less comprehensive set of criteria (de Bruin et al., 2005). In the maintenance domain, maturity models are used to assess existing management practices and processes. Indeed, to enhance a company's maintenance performance, its most significant weaknesses must be systematically identified to allow for the implementation of needed improvements (Schuh et al., 2010). Therefore, maturity models can also be used to assess maintenance sustainability, maturity and readiness, and suggest actions and practices for achieving more sustainability-oriented goals and decisions in manufacturing systems.

However, our literature review highlighted the lack of such a maturity model. Thus, this study was conducted to contribute to this research field by developing a maturity model that measures both the maturity and the sustainability maturity of maintenance processes, thereby giving an idea of the impact of maintenance activities on the three dimensions of sustainability.

This paper is organised as follows. Section 2 reviews literature on previously developed maintenance maturity models; Section 3 presents the conceptual model and the tool that we developed for assessing maintenance maturity and sustainability in manufacturing contexts. Section 4 discusses the application of the model in real case studies. Finally, Section 5 concludes this paper and suggests topics for future research.

Literature review

Objective, research questions and method

A systematic review of the literature was conducted, allowing a replicable, scientific and transparent process (Tranfield et al., 2003). The search strategy is then reported in the following.

First, the objective was set, i.e., identify all the tools, methods and models presented in literature for maintenance maturity assessment in manufacturing systems and determine if they also assess maintenance sustainability maturity. Thus, the following research questions (RQs), to which the study aims to answer, were defined:

RQ1. *What are the models/methods/tools provided in the literature that assess the maintenance maturity of manufacturing systems?*

RQ2. *In these models/methods/tools, are the sustainability maturity levels of the maintenance processes also assessed?*

The review was conducted in October 2021 in the Scopus database using the keywords "maintenance" and "maturity" in the title search field of the database. In the first screening step, the title and the abstract of each paper retrieved from the search were read; the paper was excluded if it was off-topic (e.g., if it was on software maintenance maturity models) or included if it was consistent with the objective and the RQs of this study. The included papers were then read fully in the second screening step to finalise the selection of papers for review. Finally, the references of the papers were checked to see if additional papers can be evaluated and included in the analysis according to the objective of study.

Literature review results

A total of 39 papers were initially selected from the database. After the full reading of the text, nine articles were retained because they were fully coherent with the objective and the RQs of our study. Moreover, two papers from the references of the retained papers were added. Therefore, a total of 11 papers were finally selected. The limited number of included papers was a result of the highly focused objective and RQs.

The main characteristics of the selected papers are reported in Table 1. It will be noticed that in the selected papers, the *dimensions* term is often interchangeable with other terms such as *criteria*, *key process areas* and *classes*. Therefore, we generalise with the term *dimensions* because it is the most frequently used in the papers.

Table 1
Characteristics of the selected papers

Authors (year)	Title	Objective	Method of assessment	Dimentions considered in the maturity model	Maturity level
Hauge & Mercier (2003)	Reliability-Centered maintenance maturity level roadmap	A roadmap for assessing Reliability Centred Maintenance (RCM) maturity and improving the management of RCM processes	Not specified	(1) analysis; (2) analysis documentation; (3) metrics; (4) mentoring & facilitation; (5) training; and (6) living process	5
Schuh, Lorenz, Winter & Gudergan (2010)	The house of maintenance: Identifying the potential for improvement in internal maintenance organisations by means of a capability maturity model	Assessment tool that identifies shortcomings in maintenance performance & potentials for improvement	Workshop + Questionnaire	(1) Information & knowledge management; (2) maintenance object; (3) materials management; (4) partnerships; (5) maintenance control; (6) maintenance organisation; (7) maintenance policy & strategy; (8) customer; and (9) maintenance staff	5
Kans, Ehsanifard & Moniri (2012)	Criteria and model for assessing and improving information technology maturity within maintenance	Assessment of maturity in maintenance management information technology	Not specified	(1) Maintenance Management Information technology (MMIT) utilisation level; (2) decision-making using MMIT; (3) MMIT integration; (4) Key Performance Indicator monitoring / control via MMIT; and (5) data quality in MMIT	2
Oliveira, Lopes & Figueiredo (2012)	Maintenance management based on the organization maturity level	A maturity model that allows understanding of the most appropriate strategy; maintenance tools, techniques & indicators; and potential improvements for the successful evolution of maintenance processes	Interview	(1) Maintenance strategy; (2) KPIs; (3) maintenance data systems (Computerized maintenance management system – CMMS); (4) technical competences (culture); and (5) management models	3

Table 1 [cont.]

Authors (year)	Title	Objective	Method of assessment	Dimentions considered in the maturity model	Maturity level
Macchi & Fumagalli (2013)	A maintenance maturity assessment method for the manufacturing industry	A maturity assessment method for measuring the state of maintenance practices in a company	Questionnaire + Indicators	(1) Several key process areas in each of these dimensions: (2) organisational; (3) managerial; and (4) technological	5
Chemweno, Pintelon & Van Horenbeek (2015)	Asset maintenance maturity model: Structured guide to maintenance process maturity	An asset maintenance maturity model as a structured guide to maintenance process maturity	Analytic Network Process + Indicators	(1) People & environment; (2) functional & technical aspects; (3) plant design life; (4) support; and (5) maintenance budget	5
Mehairjan, van Hattem, Djairam & Smit (2016)	Development and implementation of a maturity model for professionalising maintenance management	Measuring and monitoring the integral corporate vision of a set of multidimensional domains needed for maintenance management professionalisation	Questionnaire + Interview	(1) Organisation & processes; (2) policy & criteria; (3) information & systems; (4) data quality; and (5) performance & portfolio	3
Nemeth, Ansari, Sihn, Haslhofer & Schindler (2018)	PriMa-X: A reference model for realizing prescriptive maintenance and assessing its maturity enhanced by machine learning	Support for the implementation of a prescriptive maintenance strategy and assessment of its maturity level, facilitation of the integration of data-science methods for predicting future events and identification of action fields to reach an enhanced target maturity state and thus, higher prediction accuracy	Interview	For each step in the prescriptive maintenance process, relevant & measurable key indicators for the data analytics & maintenance dimension are derived, e.g.: (1) maintenance dimension: maintainability, reliability, availability, repair- & downtime, cost & human resource effectiveness; and (2) data analytics dimension: data quality metrics (structure, information & veracity), accuracy of failure patterns, and certainty & reliability of predictions	Not fixed
Nemeth, Ansari & Sihn (2019)	A maturity assessment procedure model for realizing knowledge-based maintenance strategies in smart manufacturing enterprises	Assessment of the maturity level of knowledge-based maintenance in smart manufacturing enterprises	Indicators	(1) Data; (2) information; and (3) knowledge	Not fixed

Table 1 [cont.]

Authors (year)	Title	Objective	Method of assessment	Dimentions considered in the maturity model	Maturity level
Oliveira & Lopes (2019)	Evaluation and improvement of maintenance management performance using a maturity model	A maturity model identifying the current state of maintenance in organisations and driving actions to increase its efficiency & effectiveness towards becoming world-class	Maintenance manager's self-assessment based on the reading of the tables' content (row: maintenance classes; column: maturity level)	(1) Organisational culture; (2) maintenance policy; (3) performance management; (4) failure analysis; (5) planning & programming of preventive maintenance activities; (6) CMMS; (7) spare parts inventory management; (8) standardisation & document control; (9) human resource management; and (10) results management (maintenance costs & quality)	5
Duque & El-Thalji (2020)	Intelligent maintenance maturity of offshore oil and gas platform: A customized assessment model complies with the Industry 4.0 Vision	Assessing the maturity of maintenance 4.0 of the offshore oil & gas platform	Questionnaire	(1) Physical space; (2) cyberspace; and (3) business layer	4

Some of the models/methods/tools selected through the review were focused on the assessment of the maintenance maturity level of specific aspects, such as of the maintenance management information technology (e.g., Kans et al., 2012; Nemeth et al., 2019), or of specific maintenance strategies, such as RCM (Hauge and Mercier, 2003), prescriptive maintenance and knowledge-based maintenance (Nemeth et al., 2018, 2019), and maintenance 4.0 (Duque and El-Thalji, 2020). Other models/methods/tools applied only qualitative methods, such as self-assessment of maintenance managers based on the reading of some tables provided to them (e.g., Oliveira and Lopes, 2019).

Concerning the sustainability aspects, only some authors assessed them. For example, the model that Chemweno et al. (2015) proposed allowed them to evaluate the maintenance performance in terms of its impact on the environment, safety and health, and personnel management, but the model did not give them an idea of the practices that could be implemented to increase the maturity level of the maintenance activities in these aspects. Moreover, the approach they presented was difficult to implement in manufacturing organisations, as it required companies to have a credible maintenance performance measurement framework and a clear connection between objectives and indicators, and to carry out the analytic network process with experts.

Considering the remaining analysed literature, no maturity method or model provided a sustainability maturity assessment of several maintenance processes. Therefore, this study attempted to fill this gap by proposing a maintenance maturity assessment model that also measures the maturity of maintenance practices in supporting sustainable operations in manufacturing systems.

Among the analysed papers, we used the structure of the maturity method that Macchi and Fumagalli (2013) developed as the reference for the design of our proposed model. We chose it because at the end of the review analysis, its results were the most complete (i.e., all the organisational, technological and managerial processes were considered), aside from which the method combined the qualitative (questionnaire) and quantitative (indicators) approaches, which guaranteed, on the one hand, easy interaction with the maintenance managers (through the questionnaire) and, on the other hand, easy summarising of their answers (through the indicators).

A maintenance maturity assessment model for sustainable manufacturing

The conceptual model

A model for assessing and defining the maturity and sustainability of maintenance processes in the manufacturing domain is presented in this section. The model defines the level of maturity and sustainability of maintenance processes and, therefore, their individual opportunities for improvement.

Figure 1 shows the model structure developed by Macchi and Fumagalli (2013). The main difference between our model and theirs is our introduction of a sustainability maturity level into each maintenance dimension and our definition of new process areas to cover a wider range of practices that are significant in the measurement of maintenance maturity and sustainability.

As reported in Figure 1, the main concepts of the model are the *maintenance maturity level* (MML), *sustainability maturity level* (SML), *maintenance dimension* (MD) and *process area* (PA). Their definitions and descriptions are provided in Table 2.

The three MDs are as follows.

1. Managerial: The aim of this dimension is to measure the managerial capability of the maintenance department to monitor the company's assets (i.e., their useful life and operating status) and to manage their risks (economic, social and environmental).
2. Organisational: This dimension aims to evaluate the training and competences of the maintenance workers and production personnel responsible for the maintenance of the basic conditions of the company's assets. Moreover, this dimension is in charge of the measurement of the relationships between the maintenance department and its suppliers of spare components, equipment or services; the department's criteria for choosing suppliers (i.e., know-how, performance, and product quality or offered service); the interest of the maintenance department in obtaining environmental and safety certifications; and the collaboration and relationship of the maintenance department with other departments.

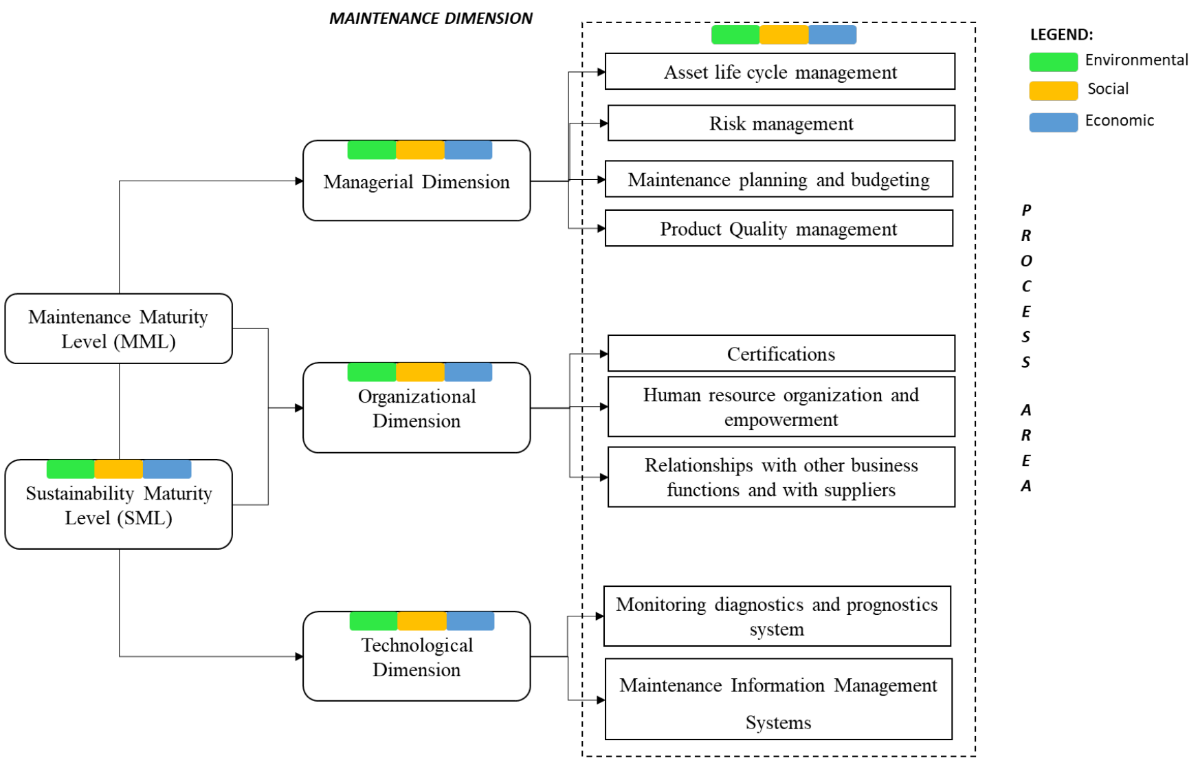

Fig. 1. Model structure

Table 2
Main concepts of the model structure

Maintenance Maturity Level	Sustainability Maturity Level	Maintenance Dimension	Process Area
Maturity level of maintenance practices (mainly based on technical aspects). Can be calculated at different levels: the aggregated level, maintenance dimension level and process area level.	Sustainability maturity level of maintenance practices (considering the economic, environmental and social aspects). Can be calculated at different levels: the aggregated level, the maintenance dimension level and the process area level.	Capability of maintenance department in a specific scope/dimension. Three maintenance dimensions are considered: Managerial, Organizational, Technological.	Capability of maintenance department in a specific process area belonging to a specific maintenance dimension. Nine process areas are considered: Asset life cycle management, risk management, maintenance planning and budgeting, product quality management, certifications, human resource organization and empowerment, relationships with other business finctions and with suppliers, monitoring diagnostic and prognostic systems, maintenance information management systems.

3. Technological: This dimension evaluates the technological capability of the maintenance department to use tools, as Computerized maintenance management system (CMMS), Enterprise Asset Management (EAM), Enterprise Resource Planning (ERP), and the deployment and full integration of maintenance information management systems (MIMS) in the organisation. Also, this dimension evaluates the adoption of monitoring, diagnostic and prognostic systems.

To properly define the process areas (PAs), the available literature on maintenance maturity models was reviewed, and recurrent meetings and interviews were conducted with maintenance experts, who gave suggestions for the proper design of the model and the definition of the PAs, which were then assigned to the three MDs.

1. The *managerial dimension* includes all the PAs concerned with the planning (i.e., *maintenance planning and budgeting*) and management of assets during their life cycle (*asset life cycle management*, including *risk and product quality management*).
2. The *organisational dimension* considers the PAs related to the certifications and the management and improvement of internal and external relationships as well as the continuous training and education of human resources (*relationships with other operating departments and suppliers, and human resource organisation and empowerment*).
3. The *technological dimension* includes all the PAs related to the use of MIMS and tools for monitoring and prognostics. The objective is not only to evaluate the presence of these systems but also to measure if the company is effectively using these systems.

The MML is associated with each PA depending on how the processes included in the PA are managed and executed. An MML scorecard is proposed in Table 3.

Table 3
Scorecard defining the scales of the maintenance maturity levels (MMLs) of the process areas

MML	Description
MML-5 (Optimising)	The process is managed with continuous improvement guaranteed.
MML-4 (Quantitatively Managed)	The process is well documented and standardised. Process performance is measured and analysed to reduce waste.
MML-3 (Defined)	The process is defined and well managed.
MML-2 (Qualitatively Managed)	The process uses effective initial maintenance management practices that are discretely documented, but there are shortcomings in the organisational, managerial and technological areas.
MML-1 (Basic)	The process does not use effective maintenance management practices and they are not documented; the process cannot be reproduced and is unpredictable.

As for the MML, an SML is associated with each PA to evaluate the impact of the maintenance processes on the economic, environmental and social dimensions of sustainability. Several aspects are considered for each sustainable dimension (Figure 2).

Seven SMLs are identified in Figure 3. The SML value depends on the sustainable dimensions and aspects (Figure 2) considered in each dimension. For example, if no sustainability dimension is considered, the corresponding SML will be SML-1; if all the possible economic aspects but only some social and environmental aspects are considered, the corresponding SML will be SML-5.

According to the literature and experts in the field of maintenance and sustainability, the first sustainable dimension considered is the economic (SML-2),

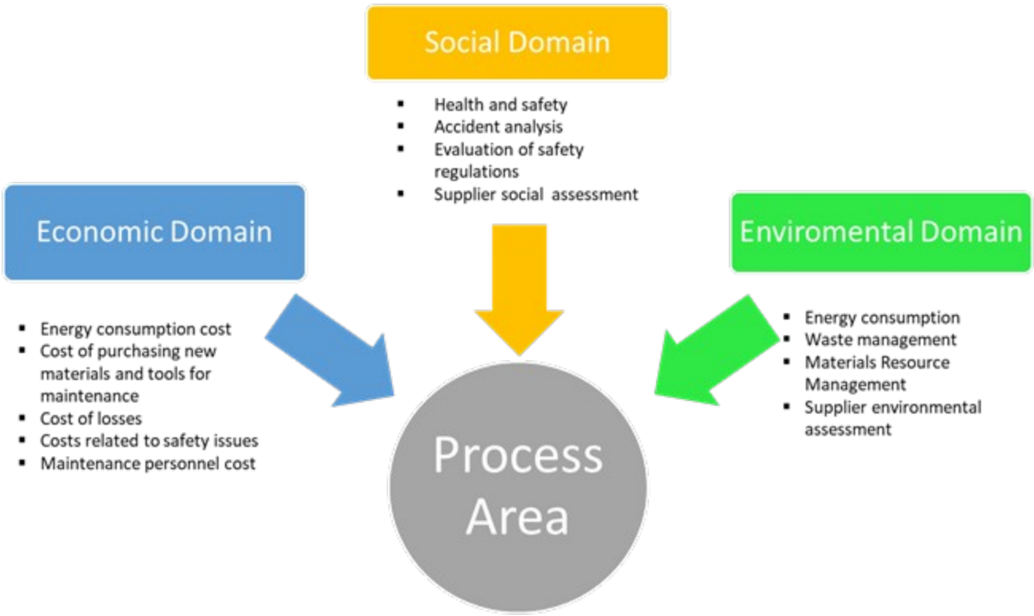

Fig. 2. Economic, social and environmental aspects of the measurement of the sustainable maturity index

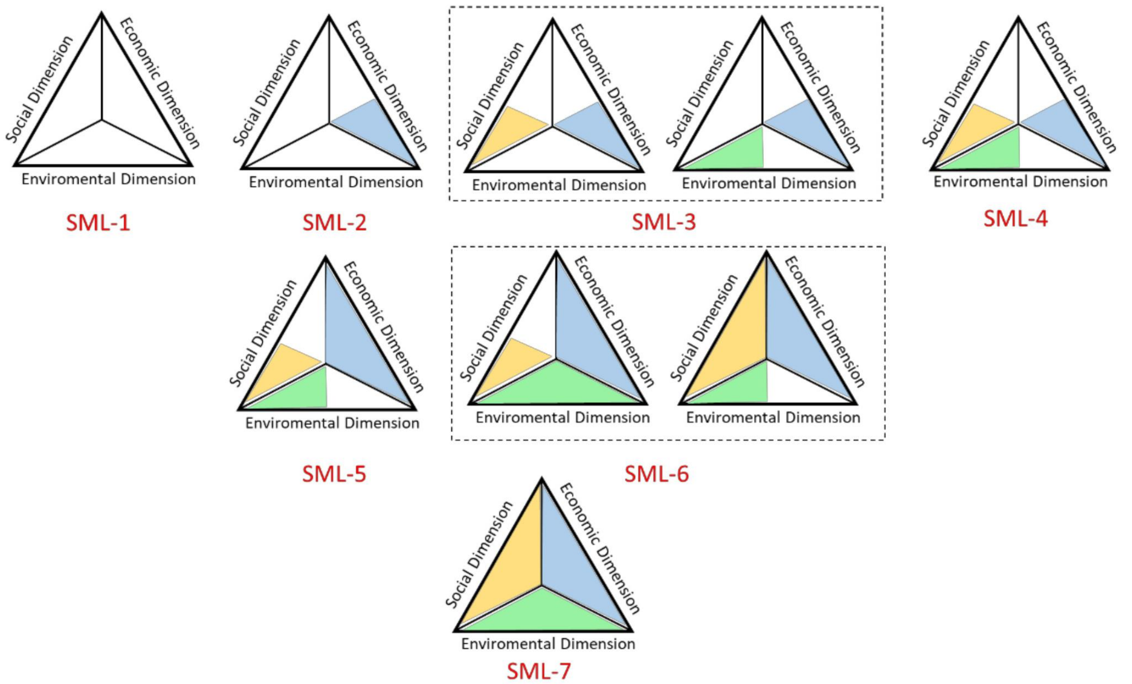

Fig. 3. Sustainability maturity levels (SMLs)

Table 4
Scorecard defining the scales of the sustainability maturity levels (SMLs) of the process areas

SML	Description
SML-7 (*Strong sustainability*)	The process has reached complete maturity in the economic, social and environmental dimensions.
SML-6 (*Strong economic responsibility and strong social or environmental responsibility*)	The process has reached complete maturity in the economic dimension and complete maturity in the social or environmental dimension.
SML-5 (*Strong economic responsibility and weak social & environmental responsibility*)	The process has reached complete maturity in the economic dimension, while only some aspects of the social and environmental dimensions are considered.
SML-4 (*Weak sustainability*)	The process considers only some economic, social and environmental aspects, but at least one aspect for each sustainability dimension.
SML-3 (*Weak economic & social or environmental responsibility*)	The process considers only some economic and social aspects or some economic and environmental aspects.
SML-2 (*Weak economic responsibility*)	The process considers only some economic aspects.
SML-1 (Not sustainable)	The process is not sustainable.

followed by the social and the environmental. In other words, the maintenance practices are first aimed at reducing costs, and then, can be improved to achieve social and/or environmental goals. For this reason, the proposed model considers the environmental and social dimensions in maintenance practices only if the economic dimension was already considered. For example, a company that monitors its maintenance activities first assesses its technical and economic indicators, and then, monitors its environmental indicators or factors related to the working conditions of the maintenance equipment operators.

The sustainability assessment is carried out considering that the practices used in the PAs can have an impact on a specific sustainable dimension. Therefore, an SML is associated with each PA. An SML scorecard is proposed in Table 4.

The assessment tool

The MMLs were measured by submitting a set of questions to the respondents. Therefore, a questionnaire was developed to properly collect data, perform a statistical analysis and realise the reports.

In the following section, the structure of the questionnaire used in the model is provided.

Questionnaire

A set of questions for each PA and closed answers for each question were identified from the literature analysis (e.g., Macchi and Fumagalli, 2013; Wireman, 2014) and from the semi-structured interviews with the maintenance experts, who verified the completeness of the questions with respect to the PAs and the MDs.

The questions address the practices used by the company to manage specific processes. A brief description of the issues treated in the questions and the final number of questions for each PA, are presented in Table 5. The answers are ranked according to descriptions that ranged from the absence of effective maintenance practices, which are generally not *mature* and not *sustainable*, to good or best practices, which generally demonstrate a high SML and MML, and therefore, are aligned with the scorecards presented in Tables 3 and 4.

In particular, the highest MML and SML are assigned if the adopted practices are continuously optimised (MML-5 in Table 3) with a strong positive impact on all three dimensions of sustainability (SML-7 in Table 3), and the lowest MML and SML are assigned when the used practices are ineffective (MML-1 in Table 2), with a consequently negative impact on all the three dimensions of sustainability (SML-1 in Table 4).

In Figure 4, an example is provided for better understanding. The question measures the level of adoption of autonomous maintenance, a practice included in the Total Productive Maintenance methodology. The practice includes cleaning–lubrication–tightening–adjustment–inspection–readjustment activities on production equipment, performed by production operators. One of four closed answers can be chosen, and each answer is associated with an MML

Table 5
Main issues considered and number of questions for each process area

Maintenance dimension	Process area	Issues considered	Number of questions
Managerial	Asset life cycle management	• use of failure analysis tecniques and root cause analysis tools (e.g., FMECA, Ishikawa diagram); • use of techniques for managing asset life cycle; • collection of information and data related to the assets (e.g., downtime, failures, quality, safety of people, equipment and environment) and measurement of asset performance.	21
	Risk management	• application of risk analysis practices (e.g., Reliability Availability Maintainability Safety (RAMS), Reliability Centered Maintenance (RCM)).	
	Maintenance planning and budgeting	• maintenance policies and practices; • management of maintenance work orders; • planning, definition and monitoring of maintenance budget; • investment in projects with an expected positive impact on economic, social and enviromental issues.	
	Product quality management	• measurement of maintenance impact on quality standards (e.g., percentage of wastes and reworked, non-quality costs, disservice provided); • use of techniques for non-conformity management (e.g., QAmatrix, 5 Whys for 0 defects).	
Organisational	Certifications	• organisation for the achievement of certifications (e.g., ISO 9001, ISO 55001, ISO 14040).	12
	Human resource organization and empowerment	• training of maintenance personnel; • monitoring of maintenance personnel performance; • adoption of tools for managing maintenance personnel skills (e.g., skill matrix); • application of maintenance standard procedure for carrying out maintenance activities (e.g., SOP).	
	Relationships with other business functions and with suppliers	• collaboration between production and maintenance personnel; • organization of meetings involving different company departments for sharing information; • criteria considered for the suppliers selection and assessment.	
Technological	Monitoring diagnostic and prognostic systems	• adoption of tools for real time monitoring of asset health status; • presence of alarm systems for signaling asset failures; • definition and measurement of specific indicators to monitor economic, social and environmental performance.	11
	Maintenance information management systems	• maintenance IT capability; • adoption of tools for maintenance process management (e.g., CMMS); • exploitation of the functionalities of MMISs, if used.	

and an SML based on the scorecards defined in Tables 3 and 4. When autonomous maintenance practices are not adopted and there is no awareness of the relevance of this practice, this has a negative impact on sustainability. Therefore, the following maturity levels are assigned to the corresponding answers: MML-1 and SML-1. The performance of basic cleaning activities demonstrates a preliminary implementation of autonomous maintenance to reduce breakdowns, with a consequent initial involvement of pro-

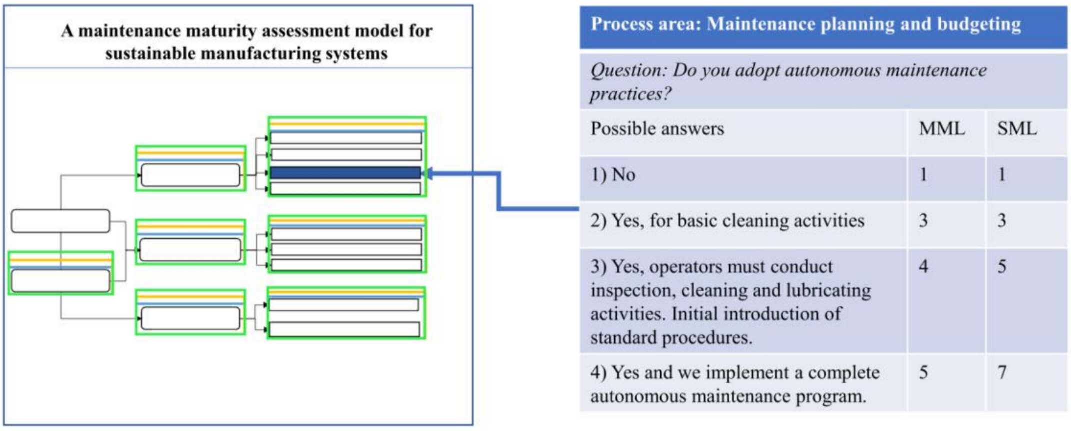

Fig. 4. Example of a question in the process area "Maintenance planning & budgeting"

duction operators who are trained with more responsibilities. Therefore, MML-3 and SML-3 are assigned, coherent with Tables 3 and 4. The execution of inspection, cleaning and lubrification activities with the initial introduction of a standardised procedure shows a strong awareness of the relevance of the practice, as well as the importance of introducing standardised and managed procedures with the consequent achievement of some benefits in the environmental dimension (less waste and rework) and the social dimension (greater involvement and training of the personnel) and strong benefits in the economic dimension (e.g., increased asset availability and productivity and reduction of losses, with consequent strong savings). Therefore, MML-4 and SML-5 are assigned. The implementation of a complete autonomous maintenance programme demonstrates full maintenance maturity with a consequent strong positive impact on all the three dimensions of sustainability. Therefore, MML-5 and SML-7 are assigned.

The assessment procedure: Mathematical formulation

The maturity and sustainability assessment procedure is described as follows.

A weight w_j can be assigned to each PA and a weight w_i, to each MD. The relevance of each PA and MD depends on the company goals and the industrial sector. These weights can be set by the interviewers, considering that

$$\sum_{i=1}^{n} w_i = \sum_{j=1}^{p} w_j = 1.$$

The variable q identifies the question, k is the total number of questions in each PA_{ij}, the $(\text{maturity level})_{jq}$ is the level associated with the question q of PA_{ij}, and p is the number of PAs in MD_i. The variable i refers to the i-th MD, and n, to the total number of dimensions.

$$\mathrm{PA}_{ij} = \sum_{q=1}^{k} w_j * \left(\frac{\text{maturity level}_{jq}}{k}\right), \qquad (1)$$

$$\mathrm{MD}_i = \sum_{j=1}^{p} w_i * \left(\frac{(\mathrm{PA})_{ij}}{p}\right). \qquad (2)$$

Finally, an aggregate maintenance maturity index (MMI) can be evaluated as the average of MD_i [equation (3)].

$$\mathrm{MMI} = \sum_{i=1}^{n} \frac{(\mathrm{MD})_i}{n}. \qquad (3)$$

A sustainability maturity index [SMI; equation (4)] is calculated based on the answers of the respondents, to each of which corresponds an SML for the questions for which it is appropriate to assess the impact of the maintenance processes on sustainability. For the questions that refer to practices whose application has no impact on sustainability, the answers are evaluated only in terms of the maintenance maturity, and no SML is assigned.

$$\mathrm{SMI} = \sum_{q=1}^{r} \frac{\text{Sustainability level}_q}{r}. \qquad (4)$$

The variable r identifies the set of questions, among the total number of questions k, to which an SML is assigned. Of course, as for the maintenance maturity, also in this case, it is possible to calculate a specific sustainability index for each MD as the mean of the sustainability indices achievable for all the PAs included in each MD.

Model output

The model output consists of one of five MMLs and one of seven SMLs, as shown in Tables 6 and 7, respectively. Therefore, based on the MMIs and SMIs reached by the respondents, it is possible to understand to which MML and SML the organisation is

Table 6
Maintenance maturity levels (MMLs)

MML	Description
MML 1	There is no awareness of the relevance of asset life cycle management, risk management practices and product quality management. Moreover, no maintenance budget is set, and failure-based maintenance is adopted. No training activities of maintenance personnel and no skills and safety analysis are carried out. No communication among operating departments and criteria for selecting suppliers are well defined. No certification has been achieved. No monitoring, diagnostic and prognostic systems, and maintenance information management systems (MIMS) are adopted.
MML 2	The maintenance stakeholders are becoming aware of the need to introduce asset life cycle management, risk management practices and product quality management. Moreover, a periodic maintenance policy is adopted. Some training activities of maintenance personnel as well as skills and safety analyses are planned in the short to medium terms. The maintenance stakeholders are becoming aware of the need to share information with other operating departments and select suppliers based on well-defined criteria. Data collection and monitoring are performed on paper, and diagnostic and prognostic activities are not performed.
MML 3	Some asset life cycle management practices (e.g., end-of-life management practices and initial asset data collection) and risk management practices are implemented. Preliminary analyses are conducted to evaluate the impact of maintenance activities on product quality. Periodic maintenance is the mainly adopted policy, but a condition-base maintenance (CBM) is introduced for some critical components. Training activities and skills and safety analyses are conducted but not systematically. The criteria for selecting suppliers have been identified. Meetings between maintenance and other operating departments are organised. Support tools are deployed for managing data (e.g., Excel and Access), and diagnostic and prognostic systems are introduced but not well managed.
MML 4	Most asset and maintenance data are collected and monitored along the asset life cycle for building strategic indicators; risk management practices are well defined; and analyses are performed to identify the impact of maintenance activities on product quality. Periodic maintenance is mainly adopted, a CBM is introduced for some critical components, and the asset health status is monitored (to introduce a predictive maintenance program). Training activities are conducted based on the skill levels of the maintenance personnel, and safety analyses are performed. A system for monitoring suppliers' performance is defined. Meetings between maintenance and other operating departments are frequently organised. Autonomous MIMS (e.g., CMMS) are deployed to manage data collected through asset integrated technologies. Diagnostic and prognostic systems are properly implemented.
MML 5	There is a strong awareness of the relevance of asset life cycle management, risk management, and product quality management, and related practices are standardised. Based on the functional condition of the assets and specific studies conducted on the asset components, the most suitable maintenance policy is adopted and a maintenance budget is defined. Well-standardised training activities of maintenance personnel and skills and safety analyses are carried out. Complete information sharing is achieved, and periodic meetings are scheduled. Suppliers' performance is continuously monitored and analysed. Several certifications have been achieved. Advanced MIMSs are completely integrated in the enterprise management system and data are collected in real time through smart technologies. Diagnostic and prognostic systems are properly implemented and continuously updated.

Table 7
Sustainability maturity levels (SMLs)

SML	Description
SML 1	Because there is no awareness of the relevance of asset life cycle management, risk management and product quality management; no adoption of failure-based maintenance; and no well-defined maintenance budget, training activities of maintenance personnel and skills and safety analysis, there is a negative impact on the economic, environmental and social aspects.
SML 2	Maintenance stakeholders are becoming aware of the need to introduce some maintenance management practices, thereby achieving an initial economic advantage (e.g., in terms of savings).
SML 3	The implementation of some asset life cycle management practices (e.g., end-of-life management practices and initial asset data collection on paper), preliminary analysis to evaluate the impact of maintenance activities on product quality, definition of some factors or indicators to measure maintenance performance and adoption of periodic maintenance allows for the achievement of some economic and environmental or social benefits.
SML 4	Some critical asset and maintenance data are collected and monitored along the asset life cycle; some risk and safety management practices are defined; and analysis is occasionally performed to identify the impact of maintenance activities on product quality. Periodic maintenance is mainly adopted, and training activities and skills and safety analysis are conducted but not systematically. This enables the achievement of some benefits in all three dimensions of sustainability (e.g., improvement of health and safety of employees, reduction of resources consumption and economic savings).
SML 5	Some critical asset and maintenance data are collected and monitored along the asset life cycle; some risk and safety management practices are defined; and analysis is occasionally performed to identify the impact of maintenance activities on product quality. Periodic maintenance is mainly adopted, but the CBM is introduced for some critical components, and a proactive maintenance policy is introduced for some critical assets, the training activities, skills and safety analysis are conducted but not systematically, and support tools are deployed for managing data (e.g., Excel and Access). This enables the achievement of some benefits in the environmental and social dimensions and strong benefits in the economic dimension (e.g., increased asset availability and productivity, and reduction of losses with consequent savings).
SML 6	Some critical asset and maintenance data are collected and continuously monitored along the asset life cycle; some risk and safety management practices are defined; and analysis is occasionally performed to identify the impact of maintenance activities on product quality. Periodic maintenance is mainly adopted, but the CBM is introduced for some critical components; and a proactive maintenance policy is introduced for some critical assets, training activities as well as skills and safety analysis are conducted systematically for both maintenance and production employees, and support tools are deployed for managing data (e.g., Excel and Access). These enable the achievement of some strong benefits in the environmental dimension (e.g., recovery, recycling and remanufacturing of material resources) or the social dimension (e.g., improvement of skills and major employee involvement) and strong benefits in the economic dimension (e.g., increased asset availability and productivity, and reduction of losses with consequent savings).
SML 7	There is a strong awareness of the relevance of asset life cycle management, risk management and product quality management, and practices are standardised. Based on the functional condition of assets, the most suitable maintenance policy is adopted and a maintenance budget is defined. Well-standardised training activities of maintenance personnel as well as skills and safety analysis are carried out. Complete information sharing is achieved and periodic meetings are scheduled. Suppliers' performance is continuously monitored and analysed based on economic, social and environmental criteria. MIMSs are completely integrated in the enterprise management system and data are collected in real time through smart technologies. Diagnostic and prognostic systems are properly implemented and continuously updated. These enable the achievement of strong benefits contextually in all three sustainability dimensions (e.g., improvement of skills, major employee involvement, increased asset availability and productivity and reduction of losses with consequently strong economic, environmental and social 'savings').

closer (i.e., where the organisation is positioned in terms of maturity). This enables understanding of the practices that should be undertaken to reach higher levels.

Application of the model

The proposed model was tested on three companies located in the city of Salerno, in Italy.

To prepare the organisations to the content of the survey, an email reporting the objective of the study, the structure of the questionnaire, the number of questions and the time needed for the compilation was arranged. The questionnaire was therefore sent to the companies by email using the Google Forms application. Moreover, the stakeholder who had a complete vision of the maintenance processes (e.g. the manager of maintenance department) was asked to compile the accomplished questionnaires.

For the evaluation of the maturity and sustainability levels, the weights assigned in the mathematical formulation (Section Mathematical formulation) were equally distributed to the PAs and MDs by the interviewers.

Based on the maturity levels achieved by the maintenance department and the model output, suggestions for improvement were collected.

The sample

Three companies belonged to the food and beverage sector and, specifically, to the olive oil production sector, a particularly developed production area in southern Italy, were chosen to make a comparison among enterprises in the same domain. The three companies are located in Cilento, an area characterised by the strong presence of companies producing oil. They are micro-small companies, with a number of employees between 5 and 50, and they have a semi-structured maintenance department.

Results and discussion

The MMIs and SMIs of the interviewed companies are shown in Figure 5. All the companies showed rather low MMIs and SMIs, as they are small and thus, their maintenance function was not yet perceived as an added value. The maintenance stakeholders of Company 2 are becoming aware of the need to introduce more effective maintenance practices, and some preliminary analysis and practices have already been implemented. Consequently, Company 2 had already achieved some economic and environmental or social benefits, as demonstrated by its SMI. Moreover, Company 2 is ready to adopt practices to increase its attention to sustainability issues.

The specific results are presented for each MD (managerial, organisational and technological) in the following subsections.

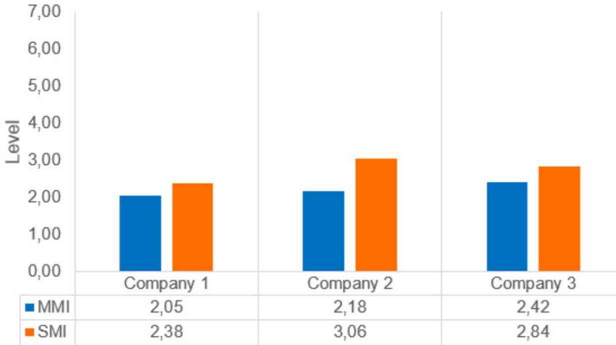

Fig. 5. Maintenance maturity index (MMI) and sustainability maturity index (SMI) values of the companies interviewed

Maintenance maturity index (MMI) and sustainability maturity index (SMI) for managerial capability assessment

Tables 8 and 9 show the MMIs and SMIs, respectively, for the four PAs involved in the evaluation of the maintenance managerial dimension: asset life cy-

Table 8
Maintenance maturity indices (MMIs) for the maintenance managerial dimension and associated process areas

MMI					
Company ID	Asset life cycle management	Risk management	Maintenance planning & budgeting	Product quality management	Managerial dimension
Company 1	1.00	2.00	2.20	1.00	1.55
Company 2	2.20	1.67	3.25	2.67	**2.45**
Company 3	1.71	1.67	2.38	1.33	1.77

Table 9
Sustainability maturity indices (SMIs) for the maintenance managerial dimension and associated process areas

SMI					
Company ID	Asset life cycle management	Risk management	Maintenance planning & budgeting	Product quality management	Managerial dimension
Company 1	1.00	2.50	4.00	1.00	2.13
Company 2	3.08	2.00	4.86	4.00	**3.48**
Company 3	2.34	2.00	3.29	2.00	2.41

cle management, risk management, maintenance planning and budgeting, and product quality management.

Some descriptions are reported as follows. For example, in the *asset life cycle management* PA, Company 1 has both the lowest MMI and SMI (MMI = 1; SMI = 1). Indeed, no tool for failure mode asset analysis had been used and no failure asset data or information had been collected. The failure analysis was based only on the experience of the maintenance personnel. As expected, the model shows that the process is not sustainable (SMI = 1), with a consequent negative impact on the economic, social and environmental dimensions.

Related to the *risk management* PA, the three companies presented the same level because all of them adopted basic risk management practices that were applied unsystematically, with a consequent positive impact on only the economic aspects (e.g., in terms of savings).

Company 2 has the highest index in almost all PAs and has both the highest MMI (2,45) and SMI (3,48). It declared that it would adopt different maintenance policies related to its assets' failure modes and apply improvement actions to increase the reliability and maintainability of its critical assets. Moreover, it is the only company among our subjects that has autonomous maintenance practices: it requires its operators to conduct inspection, cleaning and lubricating activities. Company 2 is also becoming aware of the need to introduce standardised procedures. Furthermore, it has started to invest in projects that address the economic, social and environmental aspects, such as the possibility of using environment-friendly lubricants, reduction of maintenance waste and training. These enable Company 2 to achieve high economic benefits (in terms of asset availability and productivity) and some social and environmental benefits (e.g., involvement of employees, high responsibility of operators and implementation of improvement actions that also address social and environmental aspects).

MMIs and SMIs for technological capability assessment

Tables 10 and 11 show the MMIs and SMIs, respectively, for the two PAs involved in the evaluation of the maintenance technological dimension: monitoring of the diagnostic and prognostic systems and maintenance information management systems.

Some descriptions are reported as follows. For example, all the companies have started introducing monitoring data asset tools with failure detection systems. These systems allow companies to reach an initial economic advantage (e.g., capability to detect a failure, leading to increased asset availability). Company 3 has a high value as it collects its asset data through a system interfaced with monitoring asset devices (e.g., sensors and accelerometers). This implies a higher MMI in the *monitoring, diagnostic and prognostic systems* PA (3,33). However, looking towards sustainability aspects, only Company 2 declared that it also collects and evaluates data concerning economic, social and environmental issues (e.g., energy consumption cost, consumption of renewable energy for maintenance activities, consumption of non-renewable energy for maintenance processes, and direct and indirect emissions linked to maintenance processes). For this reason, Company 2 has a higher SMI (4,75). No company showed a high value in the *maintenance information management systems* PA, however, as none of the companies used a computerised maintenance management system for managing maintenance data and information, and only Company 3 had started deploying informative support tools (e.g., Excel and Access) for managing maintenance data, due to which it has a high MMI (3). This allows the company to obtain an initial economic advantage (e.g., in terms of savings).

Table 10
Maintenance maturity indices (MMIs) for the maintenance technological dimension and associated process areas

Company ID	MMI		
	Monitoring, diagnostic & prognostic systems	Maintenance information management systems	Technological dimension
Company 1	3.00	2.00	2.50
Company 2	2.33	2.00	2.17
Company 3	3.33	3.00	**3.17**

Table 11
Sustainability maturity indices (SMIs) for the maintenance technological dimension and associated process areas

Company ID	SMI		
	Monitoring, diagnostic & prognostic systems	Maintenance information management systems	Technological dimension
Company 1	2.50	2.50	2.50
Company 2	4.75	1.00	**2.88**
Company 3	2.75	2.50	2.63

MMIs and SMIs for organisational capability assessment

Tables 12 and 13 show the MMIs and SMIs, respectively, for the three PAs involved in the evaluation of the maintenance organisational dimension: human resource organisation and empowerment, relationships with other departments and with suppliers, and certifications.

Some descriptions are reported as follows. For example, concerning the human resource organisation and empowerment PA, all the companies have the same MMI ($\cong 2$) and SMI ($= 2.50$). Indeed, no company regularly performs technical training of its maintenance personnel; only Company 3 stated that it periodically trains its maintenance personnel. No company uses tools and techniques to assess the skills and training needs of its maintenance personnel; only Company 3 stated that it performs preliminary accident analysis related to maintenance activities. All the companies are not properly aware of the relevance of human resource organisation. They had started to introduce some preliminary activities but not systematically. Thus, they all have a low SMI for this PA.

Table 12
Maintenance maturity indices (MMIs) for the maintenance organisational dimension and associated process areas

MMI				
Company ID	Human resource organisation & empowerment	Relationships with other business finctions & with suppliers	Certifications	Organisational dimension
Company 1	1.80	3.00	1.50	2.10
Company 2	1.80	1.00	3.00	1.93
Company 3	2.00	4.00	1.00	**2.33**

Table 13
Sustainability maturity indices (SMIs) for the maintenance organisational dimension and associated process areas

SMI				
Company ID	Human resource organisation & empowerment	Relationships with other business finctions & with suppliers	Certifications	Organisational dimension
Company 1	2.50	Not applicable	2.50	2.50
Company 2	2.50	2.00	4.00	2.83
Company 3	2.50	7.00	1.00	**3.50**

Related to the *relationships with other departments and with suppliers* PA, Company 3 has the highest MMI and SMI (MMI = 4 and SMI = 7). It takes care of the relationships between its operating departments, organising periodic meetings involving all such departments to discuss different issues and to make everyone aware of the decisions made. Moreover, Company 2 declared that its maintenance and production personnel collaborate excellently in improving their communication and increasing the company's productivity and asset availability. Company 3 also considers environmental and social criteria in choosing suppliers, and thus, monitors and analyses its suppliers' performance based not only on economic criteria but also on social and environmental criteria. For this reason, Company 3 has the highest SMI (7). To clarify, for this PA, the result 'not applicable' means that Company 2 did not answer the questions for the evaluation of the sustainability aspects.

All the companies already have environmental, quality and safety certifications (e.g., ISO 9001, ISO 55001 and ISO 14040), but only Company 2 planned to obtain further certifications in the environmental, quality and safety fields in the short term. This shows the maturity to organise and manage maintenance and operations more effectively achieving several benefits guaranteed by ISO, like costs reduction, better planning and controlling of maintenance, increase of asset availability, improvement of human resources skills, better environmental performance, reduction of incidents, improvement of company image and brand, saving of raw materials and energy, improvement of environmental compliance. Hence, this reveals also the company commitment towards the improvement of sustainability-related performance.

Conclusions

The practices used in the maintenance management processes have significant impacts on sustainability, directly through their execution and indirectly through their impacts on the production process and on the quality of the manufactured product due to maintenance efficiency or inefficiency. Thus, there is a general need for manufacturing companies to be supported in the identification of their MML to enable them to improve their maintenance processes. MMLs are useful in assessing maintenance processes and identifying a company's most significant weaknesses in its maintenance organisation so that it could identify and implement needed improvements.

The literature review conducted in this paper in the field of MMLs showed that no maturity method or model provides a sustainability maturity assessment of the organisational, technical and managerial maintenance areas. Therefore, a model was proposed for assessing the maturity and sustainability of maintenance processes and suggesting improvement actions, maintenance strategies and investments that could be adopted to achieve more sustainability-oriented goals and decisions in manufacturing systems.

The main characteristics of the developed model are as follows.

- First, the model quantitatively and qualitatively measures the contribution of existing maintenance practices to sustainability performance through the assignment of a numerical level and a related explanation of the attained level. Therefore, the model can make maintenance and production stakeholders more aware of the maturity of their maintenance practices and the significant impacts of their maintenance processes on sustainability.
- Second, the model output (i.e., the matrix reported in Tables 6 and 7) allows understanding of the actions and strategies that could be undertaken for the improvement and the sustainability of key maintenance PAs (starting from the level achieved by the company) to continuously increase the company's maintenance maturity and sustainability standards. Indeed, the model supports companies in defining their improvement prioritisation path. For example, the most crucial priorities for improvement may be identified as PAs with high importance for a company as well as low levels of maturity and sustainability. Based on these insights, measures can be identified and developed to improve the company's maintenance performance, and related investments can be targeted by defining the direction of future effective improvements of maintenance practices, with a consequent positive impact on sustainability aspects.
- Finally, as Macchi and Fumagalli (2013) stated, maturity assessment can be considered a way to measure some 'leading' indicators, i.e. the MMI and SMI, that can anticipate some results measurable by means of 'lagging' indicators, as KPIs frequently adopted in maintenance for assessing maintenance and sustainability performance. From the sustainability point of view, this last point is even more important, as it is very often difficult to assess the impacts of maintenance on sustainability through synthetic KPIs. Instead, through the maturity model, it is possible to have a broader picture of the practices used in maintenance and have an idea of their impact on sustainability without necessarily defining specific indicators, using measurement systems or collecting much data, which are often difficult to measure or obtain.

The model was applied in three food and beverage companies. The results allowed us to highlight the critical issues of the companies concerning their maintenance processes. Their MMIs and SMIs allowed us to analyse how the companies' adopted maintenance practices contribute to sustainability, which made the maintenance stakeholders more aware of the need for them to implement effective strategies for more sustainable maintenance performance.

This model has some limitations, which represent the natural evolution of this study:

- Implementation of the model in other companies in different manufacturing sectors; this will allow statistical analysis in the specific sectors, the selection of the best-in-class companies and the identification of the best practices frequently adopted.
- Application of multi-criteria decision-making approaches to directly assign a weight to the PAs and the MDs based on the specific manufacturing sector. Experts in the specific manufacturing sector will be interviewed to define the weights to be assigned. This will allow comparison of companies in the same manufacturing sector and with the best-in-class companies.
- Study, formalisation and integration of the interrelations and dependencies among the process areas and the dimensions of the model to, for example, automatically detect possible inconsistent responses.

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