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Developing A Key Performance Indicator System To Integrate Sustainable Corporate Objectives Into Maintenance Using The Analytic Hierarchy Process

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Abstract

Maintenance in a manufacturing company is a key function for maintaining or restoring the functional condition of the production equipment and machinery and thus for maintaining the overall efficiency of the company. Because of this role, maintenance is often considered "sustainable". As a result of regulatory requirements as well as stakeholder demands, companies are under pressure to specify their sustainability strategies. However, due to a lack of knowledge about the sustainability potential of this function, the identification of clear objectives for sustainable maintenance is often neglected. Therefore, this paper presents a performance indicator system. 133 performance indicators in the three dimensions of sustainability (economic, environmental and social) were identified in a systematic literature review. In a qualitative content analysis and inductive category building, these were then assigned to 20 different categories. The hierarchical arrangement as well as the derivation of sustainable maintenance objectives from the corporate strategy enables companies to rank the performance indicators with the help of AHP (Analytic Hierarchy Process), a tool of MCDM (Multi Criteria Decision Making). This leads to a system of performance indicators based on a company's sustainability strategy, which strengthens the focus on sustainability in maintenance functions.

Keywords

Sustainable Maintenance; Sustainability Strategy; Corporate Objectives; Multi Criteria Decision Making; Analytic Hierarchy Process

1. Introduction

Companies are facing more and more challenges, such as a lack of resources, changing customer requirements, especially in the direction of sustainability, stricter laws and regulations regarding the use of non-renewable resources, emissions or occupational health and safety [1]. The protection of people and the environment, which is the focus of the above challenges, is also called sustainability [2].

Sustainability traditionally consists of three dimensions economy, ecology and social [3,4] and is also referred to as the triple bottom line [5], as it is supposed to form the basis of entrepreneurial action. Due to the interconnectedness of the three dimensions, it is essential to consider all three in an integrative manner. Sustainability in companies is a top-down process, as the requirements for sustainable action are specified by the corporate strategy and then passed on to the individual departments [6]. Sustainability is incorporated into the corporate strategy based on stakeholder requirements [6].

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The specialist area of maintenance combines the administrative and technical measures as well as management measures to maintain and restore the functional condition of machinery and equipment. This includes measures in the area of maintenance, inspection, repair and improvement. [7] Maintenance therefore affects the productivity of companies, and their efficient and effective actions have an effect on profitability [8]. While it used to be seen only as a reactive function and cost driver, maintenance has evolved into a technologically advanced area that is an important driver of Industry 4.0 [9] but also of sustainability, as maintenance can save resources, for example [10].

Sustainable maintenance differs from traditional maintenance by considering the triple bottom line in all decisions, the inclusion of stakeholder requirements, improved process quality and the application of new technologies to increase efficiency [11]. A theoretical definition of sustainable maintenance is therefore already available, but there is a lack of methods and tools for actual implementation [10]. A group discussion conducted in January 2023 with maintenance experts from the process industry revealed that the topic is in focus for companies but is perceived as very abstract. There is a lack of concrete measures or strategies to achieve sustainability, and companies need assistance in formulating goals.

Strategies are measures to achieve goals [12]. Strategy development in companies follows four steps according to [13]. At the beginning the target picture of the company is formed. This is followed by competitive and environmental analysis, then strategy formulation and evaluation. In the last step, the strategy is implemented. During these steps, strategy controlling is also carried out to check its effectiveness and adjust it if necessary.

During strategy formulation, both overarching and functional strategies are formulated. For this paper, the focus is on the formulation of measures for sustainable maintenance, i.e. a functional strategy. To check the success of the individual measures, performance indicators can be used that are derived from the strategy development. Therefore, this paper presents key indicators that exist in the three dimensions of sustainability in maintenance. These are sorted and categorized, and then a tool is presented that enables companies to derive key figures for their functional area strategy from their corporate strategy.

2. Methods

This chapter presents the methods used, with systematic literature review in 2.1, qualitative content analysis and inductive category building in 2.2, and the Analytic Hierarchy Process in 2.3.

2.1 Systematic Literature Review

To begin, a systematic literature search was conducted to identify the existing metrics that exist on sustainable maintenance. A systematic literature search follows a transparent, reproducible, and scientific process, minimizing subjective bias through extensive searches and detailed descriptions of the procedure. This allows for the identification of high quality articles and the evaluation of existing literature on a selected topic. [14]

A literature review is conducted in three steps. At the beginning, the research is planned, although a specific research question is not necessary, however a description of the significance of the problem needs to be considered. The goal is to create a research protocol that does not limit the researcher, but minimizes bias. The second step is to conduct the literature review. In this case, the search was conducted in Web of Science and Elsevier. The search string "Maintenance AND Sustainab* AND Industr' AND (KPI OR "Performance Indicato*" was derived from the question “what are the areas of influence in maintenance with respect to sustainability”. During this systematic literature search, articles containing performance indicators of sustainable maintenance were included. The search was conducted until all performance indicators found could be assigned to an existing category through inductive category building (see also 2.2) and no new category had to be formed.

2.2 Qualitative Content Analysis and Inductive Category Building

Qualitative content analysis has the goal of analyzing documented communication, whereby in this case, as well as in the preceding literature research, a systematic, i.e. theory- and rule-guided, approach is taken. The source material, their formal characteristics as well as the concrete research question are determined in advance. [15] The used source material was selected by the systematic literature research (see also 2.1).

According to [15] the inductive category formation, which was carried out subsequently, consists of four steps. In the first step, the source material is sighted and paraphrased. This includes deleting content that is not relevant to the research question. In the following, sentence statements are generalized in the same way, although here the sentences are maintenance performance indicators. Mathematical formulas were abstracted to literal descriptions. In the next step, the first reduction, sentences with the same meaning are deleted. In this case, identical performance indicators were combined, but all sources were noted. In the fourth step, or the second reduction, paraphrases with similar meaning are combined into one. Performance Indicators with the same or similar sphere of influence are combined into one category. For clarity, these categories were then assigned to one of the three sustainability dimensions. This resulted in a category system for ordering performance indicators in maintenance to areas of influence in sustainability. When forming categories, care was taken to ensure that a category consists of a maximum of nine performance indicators, as this enables pairwise comparisons [16], that are described in the following.

2.3 Analytic Hierarchy Process

The Analytic Hierarchy Process (AHP) is a method of Multi Criteria Decision Making (MCDM). MCDM is the general term for formal approaches to help individuals or groups make decisions involving more than one decision criterion. [17,18] AHP is a method for representing and modeling problems with hierarchical structures [19]. An alternative to AHP is the Analytic Network Process (ANP), which, in addition to hierarchical structures, also incorporates interactions and dependencies of elements of a higher level with elements of a lower level. This provides a better representation of real-world problems, while increasing the complexity and scope of pairwise comparisons. [19] To keep the complexity lower and allow easy implementation in companies, AHP is selected for this paper.

AHP is particularly valuable for decisions involving qualitative, abstract, or subjective criteria. The decisions do not require the decision maker (DM) to break down a complex problem. Certain inconsistencies in the pairwise comparisons that make up the AHP are acceptable. AHP consists of three steps, beginning with identifying and organizing objectives, constraints, alternatives, and criteria. In the second step, the pairwise comparisons are performed at each level of the hierarchy, and finally the algorithm for calculating the most suitable alternative is applied. [19]

For this paper, the goal of the AHP is to make the best decision. The criteria are "economy", "ecology" and "social" are placed on the first level, the individual categories (see also 3.1) on the second level. The alternatives that are evaluated are, for example, "Reduce resource consumption" and "Reduce maintenance costs". The result of the AHP as well as an illustrative example is presented in chapter 3.2.

3. Results

The results of this research will be presented in the following chapters.

3.1 Categories and Performance Indicators

By means of qualitative content analysis and inductive category formation, various categories of sustainable maintenance could be presented. This made the areas of influence of maintenance on sustainability clear.

The categories identified are shown in Figure 1, and the performance indicators they contain are shown in tables 5-7 (Appendix).

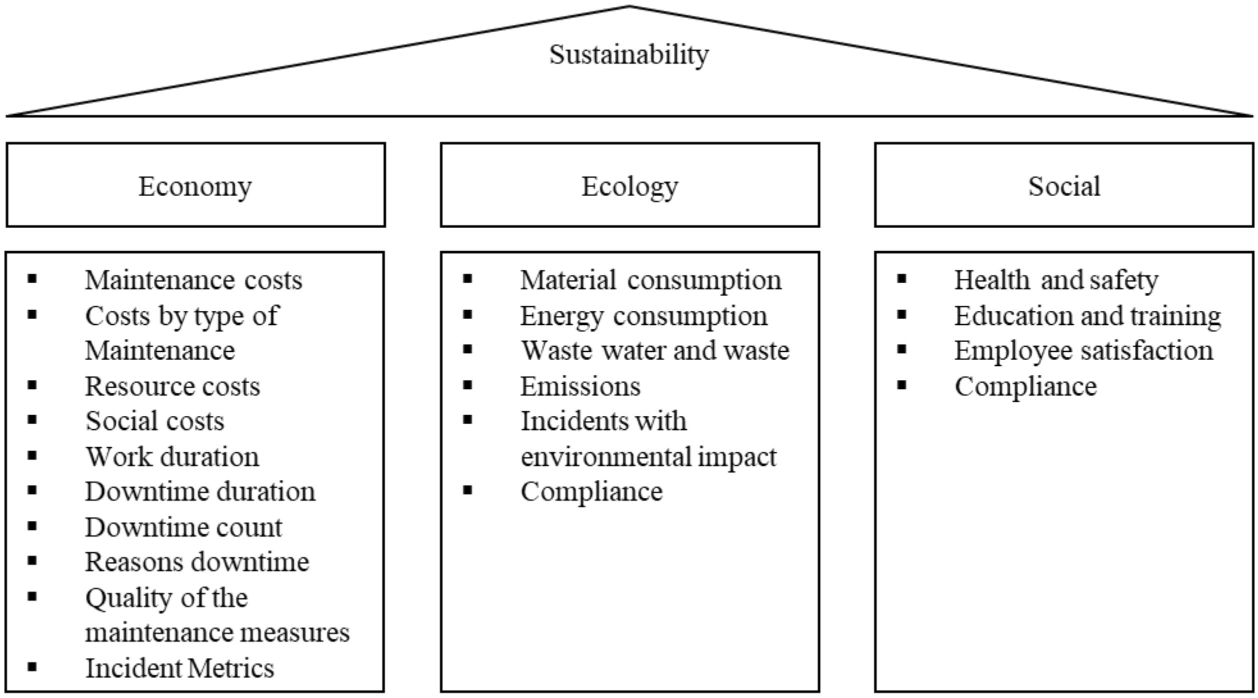

Figure 1: Categories of Sustainability in Maintenance

3.2 Analytic Hierarchy Process

Following the development of the category system for sustainability metrics in maintenance, an AHP process was developed for selecting the most important metrics for the selected sustainability strategy.

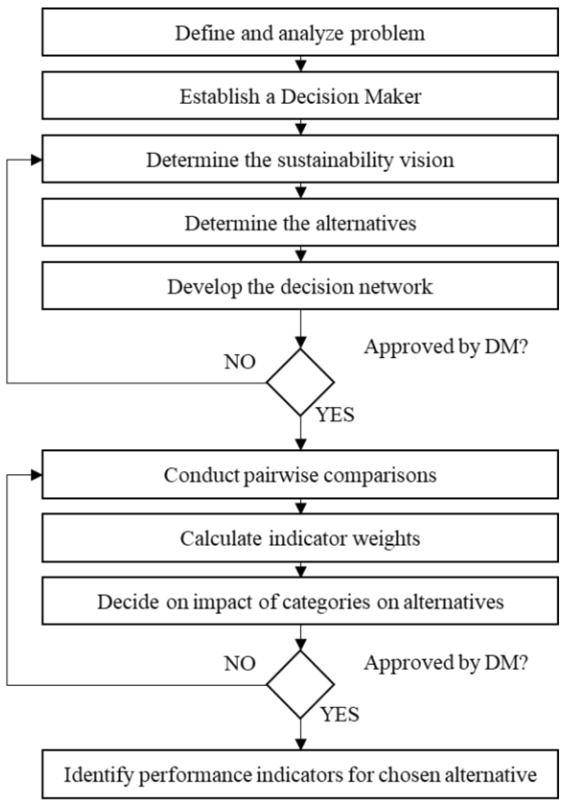

Figure 2: Process for conducting AHP following [20]

For decision making on the use of metrics, a decision model was first developed that corresponds to the categories in Figure 1. First, pairwise comparisons are conducted to determine the importance of the three dimensions: economic, environmental and social. Then, the importance of each category within the dimensions is determined by pairwise comparisons. Finally, the alternatives are evaluated with respect to the individual categories. The result shows the alternative that best fits the goal of making the best decision in terms of the categories and their importance. The procedure is illustrated in Figure 2.

As an exemplary case, this process was carried out using the "Superdecisions" software [21]. In this process, a Decision Maker (DM) was able to perform the evaluations first for the three dimensions, then for the individual dimensions. The evaluation is shown in Tables 1-3. Subsequently, possible alternatives for the decision had to be determined. In this fictitious example, the company must prioritize the set goals for sustainability and decides by means of AHP between the alternatives "reduce resource consumption" and "reduce maintenance costs". For this purpose, the alternatives were evaluated with respect to categories, for example, maintenance costs have a very large influence on the alternative "Reduce maintenance costs". The individual ratings are shown in tables 1-3.

Table 1: Normalized Ranking of Economical Criteria

Economical Criteria	**Normalized Rating**
Cost by Maintenance Strategy	0.085
Downtime Duration	0.151
Downtime Reasons	0.081
Maintenance Costs	0.223
Maintenance Metrics	0.136
Number of Downtime	0.050
Quality of Maintenance	0.054
Resource Costs	0.145
Social Costs	0.046
Working Hours	0.027

Table 2: Normalized Ranking of Ecological Criteria

Ecological Criteria	**Normalized Rating**
Incidents with environmental concerns	0.064
Compliance	0.063
Emissions	0.166
Energy used	0.270
Materials used	0.321
Sewage and Waste	0.115

Table 3: Normalized Ranking of Social Criteria

Social Criteria	Normalized Ranking
Employee Satisfaction	0.159
Health and Safety	0.046
Social Compliance	0.285
Training	0.51

As a result, based on the evaluation of the importance and the assignment of the correlation between categories and alternative, the company is recommended to pursue "Reduce resource consumption", as shown in table 4.

Table 4: Result of AHP

	Totals	Priorities
Resource Consumption	0.617	**0.614**
Reduce Maintenance costs	0.388	**0.386**

4. Conclusion

The aim of this work was to collect key performance indicators on sustainable maintenance through a systematic literature review, to sort these by inductive category building and to identify areas of influence of sustainability, and then to use AHP, a method of MCDM, to select suitable key performance indicators for a goal set by a company.

A total of 133 performance indicators were identified in the categories of economy, ecology and social, which could be classified into 20 different categories. The application of AHP is theoretically target-guiding; thus, it enables companies to identify a suitable target. The selection of the appropriate indicators through an AHP process is not directly possible as there is no overall performance indicator ranking based on the chosen alternative, however, the importance of the criteria and the evaluation of the influence of criteria on the alternatives can be used to determine which performance indicators could be considered more closely.

This study is limited by the fact that it was not tested in a real case, but only in a fictitious case. Therefore, it is recommended that the AHP process be tested in a case study and the result re-evaluated afterwards. Furthermore, the study is limited by the fact that the evaluation of the criteria should be derived from the company's mission statement, which implies that sustainability is integrated there.

For further research, it is recommended to identify a method to further improve the selection of metrics for companies, for example through the analytical network process (ANP). It is as well recommended to empirically test this model in order to allow adaptions to real-world cases, to prevent academic over-simplification or abstraction.

Appendix

Table 5: Economic Performance Indicators [22–30]

Economic criteria	Performance Indicator
Maintenance costs	Total maintenance cost/replacement value

	Return on Maintenance Invest
	Return on eco friendly Invest
	Average inventory value of maintenance material/replacement value
	Maintenance costs per unit
	Maintenance costs/sales
	(maintenance costs + cost of unavailability) / quantity Output
	Improvement in maintenance costs / Total maintenance costs
	Outage costs
	Shutdown maintenance costs / Total maintenance costs
Costs by maintenance type	Costs of planned maintenance activities
	Costs of unplanned maintenance activities
	Corrective maintenance costs / Total maintenance costs
	Preventive maintenance costs / Total maintenance costs
	Condition-based maintenance costs / total maintenance costs
	Predetermined maintenance costs / Total maintenance costs
	Expected PM costs / actual PM costs
Resource costs	Maintenance material costs / average inventory value
	Costs for processing maintenance waste
	Energy costs Maintenance measures
	Energy costs maintained systems
Social costs	Penalties for EHS violations during maintenance activities
	Penalties for EHS violations on maintained systems due to lack of maintenance activities.
	Labor costs
	Training costs
Downtime duration	Duration of planned maintenance activities
	Duration of unplanned maintenance activities
	Downtime due to short stops
	Downtime due to long stops
	Setup time between stop and start
	Total operating time/(total operating time + downtime due to planned maintenance)
Downtime count	Number of short stops
	Number of stops
	Number of long stops
	Number of planned maintenance activities
	Number of unplanned maintenance activities
Reasons downtime	Downtime due to preventive maintenance / total downtime due to maintenance
	Downtime due to predestined maintenance / total downtime due to maintenance
	Downtime due to condition-based maintenance / total downtime due to maintenance
	Downtime
	Downtime due to maintenance errors
	Downtime due to waiting for spare parts
	Downtime due to lack of training
Quality of the maintenance measures	Rework time due to lack of training
	Actual operation time/required operation time
	Percentage of maintenance tasks requiring rework

	Backlog (number of overdue tasks/number of tasks)
	Number of work orders after PM inspections
Incident Metrics	Failure rate
	Availability
	Reliability
	OEE
	MTTR
	MTBF
	MDT
	MOTBF
	MTTF
Operating time	Time required for preventive maintenance/total time for maintenance
	Time required for critical corrective maintenance/total time for maintenance
	Planned and predictive time for maintenance/total time for maintenance
	Labor hours for unplanned maintenance activities / available labor hours
	Labor hours for planned maintenance activities / available labor hours
	Planned working hours / available working hours

Table 6: Ecological Performance Indicators [23, 29-31]

Ecological criteria	**Performance Indicators**
Material consumption	biodegradable components
	recycled/reused/remanufactured materials
	direct material intensity
	Indirect material intensity
	Consumption of lubricants and cleaning agents
	biodegradable lubricants and cleaning agents
	Amount of PBT (persistent, bioaccumulative, toxic) chemicals in maintenance processes
	Amount of water needed for maintenance activities
Energy consumption	direct energy intensity ratio (within)
	Indirect energy intensity
	Reduction of energy consumption through maintenance measures
	Reduction of energy consumption of maintenance activities due to initiatives to reduce energy consumption.
	Energy emitted (heat, vibration) by maintenance processes
	Renewable energies
Waste water and waste	Maintenance waste
	Influence of maintenance waste on soil
	Soil area for maintenance activities, divided into fertile and infertile soils.
	Waste from maintained systems
	Amount of waste due to maintenance activities
	Amount of waste caused by defective maintained systems due to faulty maintenance procedures.
	Amount of liquid spilled due to maintenance activities
	Quantity of spilled liquid due to maintained systems

	Waste rate Hazardous material
Emissions	Internal GHG emissions External GHG emissions GHG Emissions Intensity Ratio Reduction of GHG emissions Emissions of ozone-depleting substances (ODS) from maintenance activities Emissions ODS due to maintained systems Emissions of (NOX, SOX, Persistent Organic Pollutants, Volatile organic compounds, hazardous air pollutants, particulate matter) due to maintenance activities Emissions of (NOX, SOX, Persistent Organic Pollutants, Volatile organic compounds, hazardous air pollutants, particulate matter) from maintained systems
Accidents with environmental impact	Noise, odor, dust, mist due to maintenance activities Number of failures due to environmental degradation caused by maintenance activities.
Compliance	Number of failures with possible impact on the environment Number of complaints, lawsuits, fines, and sanctions for non-compliance of maintenance activities with environmental laws and regulations. Number of complaints, lawsuits, fines, and penalties for non-compliance of maintained systems with environmental laws and regulations due to lack of maintenance activities. Implementation of an environmental management system Number of suppliers audited for environmental criteria

Table 7: Social Performance Indicators [23,26,27,29-31]

Social criteria	**Performance Indicators**
Health and safety	Occupational accidents Days lost due to maintenance accidents Implementation of an Occupational Health and Safety Management System Occupational accidents due to neglected maintenance Number of maintenance workers at high risk of illness or accidents due to their work Implementation of a program of continuing education for risk control to reduce the risk of occupational accidents. Personal protective equipment for maintenance activities Availability of first aid facilities Improve security performance because of security measures
Education and training	Average hours of maintenance education and training per maintainer Percentage of maintenance staff by gender receiving regular performance appraisals Percentage of maintenance staff trained in sustainability Number of training and continuing education courses conducted
Employee satisfaction	Days lost Number of complaints from employees

	Motivation level of employees
	Employee retention
	Employee satisfaction
	Number of suggestions for improvement from maintenance staff
Compliance	Number of complaints, lawsuits, fines, and sanctions for non-compliance of maintenance activities with social laws and regulations
	Number of complaints, lawsuits, fines and sanctions for non-compliance of maintained systems with social laws and regulations
	Number of customer complaints
	Number of new customers
	Number of returning customers
	Number of suppliers audited according to social criteria
	Stakeholder satisfaction

References

[1] Franciosi, C., Voisin, A., Miranda, S., Riemma, S., Iung, B., 2020. Measuring maintenance impacts on sustainability of manufacturing industries: from a systematic literature review to a framework proposal. Journal of Cleaner Production 260, 121065.

[2] Enquete-Kommission "Schutz des Menschen und der Umwelt" des 13. Deutschen Bundestages. Konzept Nachhaltigkeit, Fundamente für die Gesellschaft von morgen, 252 pp.

[3] Brundtland, G.H., 1987. Our Common Future: Report of the World Commission on Environment and Development. World Commission on Environment and Development, Oslo, 300 pp.

[4] Meadows, D.L., Meadows, D.H., Randers, J., Behrens III, W.W., 1972. The limits to growth: A report for the Club of Rome's Project on the Predicament of Mankind, 2. ed. ed. Universe Books, New York, 205 pp.

[5] Buchmüller, M., 2019. Nachhaltigkeit und Produktmodularisierung. Springer Fachmedien Wiesbaden, Wiesbaden, 383 pp.

[6] Schaltegger, S., Kleiber, O., Müller, J., 2003. Die „Werkzeuge“ des Nachhaltigkeitsmanagements. Konzepte und Instrumente zur Umsetzung unternehmerischer Nachhaltigkeit, in: Linne, G. (Ed.), Handbuch Nachhaltige Entwicklung. Wie Ist Nachhaltiges Wirtschaften Machbar? VS Verlag fur Sozialwissenschaften GmbH, Wiesbaden, pp. 331–342.

[7] DIN 31051, 2012. Grundlagen der Instandhaltung. Beuth Verlag GmbH, Berlin, 12 pp.

[8] Holgado, M., Macchi, M., Evans, S., 2020. Exploring the impacts and contributions of maintenance function for sustainable manufacturing. International Journal of Production Research 58 (23), 7292–7310.

[9] Pawellek, G., 2016. Integrierte Instandhaltung und Ersatzteillogistik. Springer Berlin Heidelberg, Berlin, Heidelberg, 440 pp.

[10] Bredebach, C., 2022. What Role Does Maintenance Play in Achieving Sustainability in Manufacturing? - A Scoping Literature Review, in: . ASME 2022 17th International Manufacturing Science and Engineering Conference. American Society of Mechanical Engineers Digital Collection.

[11] Bredebach, C., 2023. Is Sustainable Maintenance a Support- or Standalone Function? A Definition.

[12] Bea, F.X., Haas, J., 2019. Strategisches Management, 10., überarbeitete Auflage ed. UTB GmbH; UVK Verlag, Stuttgart, München, 623 pp.

[13] Welge, M.K., Al-Laham, A., Eulerich, M., 2017. Strategisches Management. Springer Fachmedien Wiesbaden, Wiesbaden.

[14] Tranfield, D., Denyer, D., Smart, P., 2003. Towards a Methodology for Developing Evidence-Informed Management Knowledge by M eans of Systematic Review. British Journal of Management 14, 207–222.

[15] Mayring, P., 2015. Qualitative Inhaltsanalyse: Grundlagen und Techniken, 12., vollständig überarbeitete und aktualisierte Aufl. ed. Beltz, Weinheim, 152 pp.

[16] Saaty, T.L., 2012. Decision making for leaders: The analytic hierarchy process for decisions in a complex world, 3. ed., 5. print ed. RWS Publ, Pittsburgh, Pa., 343 pp.

[17] Belton, V., 2002. Multiple Criteria Decision Analysis: An Integrated Approach, 1st ed. ed. Springer, Boston, 380 pp.

[18] Korhonen, P., Moskowitz, H., Wallenius, J., 1992. Multiple criteria decision support - A review. European Journal of Operational Research 63 (3), 361–375.

[19] Saaty, T.L. The Analytic Network Process.

[20] Rösner, T., Bredebach, C., 2022. Integrating the United Nations sustainable development goals into organizational strategy: A sustainability balanced scorecard approach using ANP and TOPSIS. J Sustainability Outreach 3 (1), 1–18.

[21] Saaty, T.L., 2023. Super Decisions. Creative Decisions Foundation. https://superdecisions.com/. Accessed 26 August 2023.

[22] Ferreira, S., Silva, F.J.G., Casais, R.B., Pereira, M.T., Ferreira, L.P., 2019. KPI development and obsolescence management in industrial maintenance. Procedia Manufacturing 38, 1427–1435.

[23] Lundgren, C., Bokrantz, J., Skoogh, A., 2021. Performance indicators for measuring the effects of Smart Maintenance. IJPPM 70 (6), 1291–1316.

[24] Muchiri, P.N., Pintelon, L., Martin, H., Meyer, A.-M. de, 2010. Empirical analysis of maintenance performance measurement in Belgian industries. International Journal of Production Research 48 (20), 5905–5924.

[25] Oliveira, M., Lopes, I., Rodrigues, C., 2016. Use of Maintenance Performance Indicators by Companies of the Industrial Hub of Manaus. Procedia CIRP 52, 157–160.

[26] Peach, R., Ellis, H., Visser, J.K., 2016. A MAINTENANCE PERFORMANCE MEASUREMENT FRAMEWORK THAT INCLUDES MAINTENANCE HUMAN FACTORS: A CASE STUDY FROM THE ELECTRICITY TRANSMISSION INDUSTRY. SAJIE 27 (2).

[27] Pfaffel, S., Faulstich, S., Sheng, S., 2019. Recommended key performance indicators for operational management of wind turbines. J. Phys.: Conf. Ser. 1356 (1), 12040.

[28] Rødseth, H., Strandhagen, J.O., Schjølberg, P. Key Performance Indicators for Integrating Maintenance Management and Manufacturing Planning and Control 459, 70–77.

[29] Saihi, A., Ben-Daya, M., As'ad, R.A., 2022. Maintenance and sustainability: a systematic review of modeling-based literature. JQME.

[30] Sari, E., Ma'aram, A., Shaharoun, A.M., Chofreh, A.G., Goni, F.A., Klemeš, J.J., Marie, I.A., Saraswati, D., 2021. Measuring sustainable cleaner maintenance hierarchical contributions of the car manufacturing industry. Journal of Cleaner Production 312, 127717.

[31] Franciosi, C., Roda, I., Voisin, A., Miranda, S., Macchi, M., Iung, B., 2021. Sustainable Maintenance Performances and EN 15341:2019: An Integration Proposal, in: Dolgui, A., Bernard, A., Lemoine, D., Cieminski, G. von, Romero, D. (Eds.), Advances in Production Management Systems. Artificial Intelligence for Sustainable and Resilient Production Systems, vol. 633. Springer International Publishing, Cham, pp. 401–409.

Biography

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