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THE CONCEPT OF MAINTENANCE SUSTAINABILITY PERFORMANCE ASSESSMENT BY INTEGRATING BALANCED SCORECARD WITH NON-ADDITIVE FUZZY INTEGRAL

KONCEPCJA OCENY ZRÓWNOWAŻONEGO UTRZYMANIA RUCHU Z ZASTOSOWANIEM ZRÓWNOWAŻONEJ KARTY WYNIKÓW I NIE-ADDYTYWNEJ CAŁKI ROZMYTEJ

In response to the growing sustainability concerns, manufacturing companies have to formulate measures to assess sustainable manufacturing performance, aiming at integration of sustainability aspects. Although various models and methods to assess the sustainability of production processes, and point the role of maintenance have been developed in recent years, contribution of all the elements of the maintenance to the results of sustainable production has not been comprehensively considered, since mostly financial aspects were analyzed. Taking into account this research gap, the article presents the concept of a model and procedure for assessing maintenance from the perspective of sustainable manufacturing requirements. Authors integrate three sustainability dimensions (economic, social and environmental) with Kaplan and Norton's balance scorecard perspectives as a basis to develop the model of maintenance sustainability performance assessment. For the model developed, the assessment procedure based on the paradigm of aggregate assessment was designed. The Choquet integral, based on the so-called λ – measure, was implemented to aggregate the measures. Then, the results of research on determining the importance and interactions between the perspectives and criteria for assessing sustainable maintenance in enterprises representing the automotive and food industries are presented.

Keywords: *maintenance performance, sustainable maintenance, balanced scorecard, fuzzy integral.*

W odpowiedzi na wyzwania zrównoważonego rozwoju (SD), przedsiębiorstwa produkcyjne włączają ekonomiczne, środowiskowe i społeczne wymagania SD do swoich praktyk produkcyjnych i formułują miary do oceny skuteczności podjętych działań. Pomimo, iż w ostatnich latach opracowano wiele modeli i metod oceny zrównoważonej produkcji i wskazywano w nich na rolę utrzymania ruchu, to jednak poza aspektem finansowym nie rozważano w sposób kompleksowy wszystkich elementów wkładu utrzymania ruchu w wyniki zrównoważonej produkcji. Biorąc pod uwagę tę lukę badawczą, w artykule przedstawiono koncepcję modelu i procedury oceny utrzymania ruchu z perspektywy wymagań zrównoważonej produkcji. Autorzy integrują trzy wymiary zrównoważonego rozwoju (ekonomiczny, społeczny i środowiskowy) z perspektywami zrównoważonej karty wyników Kaplana i Nortona, jako podstawę do skonstruowania modelu oceny wyników zrównoważonego utrzymania ruchu. Dla tak opracowanego modelu zaprojektowano opartą na paradygmacie oceny agregatowej procedurę oceniania. Do agregacji składników oceny zastosowano całkę Choqueta, opartą na tzw. mierze λ. Następnie przedstawiono wyniki badań pilotażowych dotyczących określenia ważności i interakcji między perspektywami i kryteriami oceny zrównoważonego utrzymania ruchu w przedsiębiorstwach branży motoryzacyjnej i spożywczej.

Słowa kluczowe: *wyniki utrzymania ruchu, zrównoważone utrzymanie ruchu, zrównoważona karta wyników, całka rozmyta.*

1. Introduction

About thirty years ago, sustainable development was defined as a 'development that meets the needs of the present without compromising the ability of future generations to meet their own needs'. One of the most important issues regarding sustainable development is sustainable manufacturing. Manufacturing operations are accompanied by various environmental and social concerns at different stages of the production processes [46]. Consequently, in the last few years, research is focusing on this new paradigm, which aims to develop sustainable production processes, innovative technologies, and new tools for assessing economic, environmental, and social impacts of industrial assets. In this context, according to [15, 32, 42, 44], maintenance function, necessary to ensure availability, reliability, and safety of industrial assets, could become one of the main pillars for sustainable manufacturing.

In response to the growing sustainability concerns, manufacturing companies have to formulate measures to assess sustainable manufacturing performance, aiming at integration of sustainability aspects. Although various models and methods to assess the sustainability of production processes and point the role of maintenance have been developed in recent years, contribution of all the elements of the maintenance to the results of sustainable manufacturing has not been comprehensively considered, since mostly financial aspects were analyzed. Taking into account this research gap, the article presents the concept of a model and procedure for assessing maintenance from the perspective of sustainable manufacturing requirements. The goal of maintenance sustainability assessment is to provide decision makers with information about current maintenance results and support them in the decision-making process regarding future directions of maintenance activities.

The authors integrate three sustainability dimensions (economic, social and environmental) with four Kaplan and Norton's balance scorecard perspectives (financial, client, internal processes and learning & growth) as a basis to develop the model of maintenance sustainability performance assessment. The assessment model developed has a two-tier hierarchical structure, the first level of which encompasses the assessment perspectives, while the second level includes the assessment criteria. The assessment procedure was developed for the model constructed as explained. The goal is to develop a synthetic indicator of sustainable maintenance performance. The assessment procedure is based on the paradigm of aggregate assessment, which stresses determination of the synthetic efficiency of an organization and company's operation on the basis of merging the particular assessment criteria into the one. The main steps of the procedure are: determining importance of the assessment criteria, defining method of assessing for each of them, and then aggregating them. Since the assessment process should also take into account a number of interrelated environmental, social and economic issues, the determination of importance and aggregation of criteria are the critical steps [14].

Hence, the second goal of the article is to select the appropriate aggregate function. In general, the properties of an aggregate function can be related to mathematical properties and behavioral properties. Mathematical properties point to formally correct aggregation of criteria, while behavioral properties express relationships between criteria including, for example, synergy and redundancy. Most of the aggregation methods presented in the literature in relation to the assessment of the sustainable development of the system have some drawbacks, namely they do not reflect the interaction between the criteria [14]. The solution to this problem in the model of sustainability assessment is to use fuzzy integrals for aggregation. Due to its characteristics, the fuzzy integral has been widely applied to the multiple attribute decision-making [8, 53]. In our application, we consider a particular case of Choquet integral, based on the so-called λ – measure.

The article is divided into three parts. The first one includes: the role of maintenance function in sustainable manufacturing environment (chapter 2); maintenance sustainability assessment framework and the fuzzy integrals with fuzzy measure as a tool for aggregation of multiple criteria (chapter 3). The second part presents the results of pilot studies on the perception of the importance and interactions between the perspectives and criteria for assessing maintenance sustainability in enterprises representing the automotive and food industries (chapter 4). The third part is the conclusions and presentation of directions for further research (chapter 5).

2. Sustainable maintenance

From a pragmatic point of view, the main goal of maintenance is to optimize the overall lifecycle of an object. In other words, ensuring maximum availability and reliability of production equipment, at minimum cost and in accordance with binding legal requirements (concerning environment, occupational safety, etc.). This goal is indicated in various maintenance definitions, e.g. [10].

Over the years, along with the production process, maintenance has evolved from the reactive function, through preventive, lean (Lean Maintenance), green (Green Maintenance), to the modern approach in which it is considered a process that should be managed in a sustainable perspective [25]. In the literature, the role of maintenance in the implementation of sustainable manufacturing goals is emphasized many times, e.g. [6, 24]. The contribution of maintenance to the economic dimension of sustainable manufacturing concerns the reduction of both maintenance costs (e.g. costs of spare parts and consumables, labor costs, etc.) and total operating costs (e.g. environmental fees, technological media costs) [5, 28, 47, 49, 55], whereas concerning the environmental dimension of the maintenance operation, i.e. planning service activities, monitoring the condition of machines and devices, it enables reduction of consumption of technological media, raw materials and materials, as well as their more efficient use [1, 3, 27, 29, 30, 52]. The social dimension concerns the relationship between the maintenance function and its stakeholders both within the company and outside of it, with particular emphasis on the employees of the technical department, production, suppliers of spare parts, service providers, etc., competence and satisfaction of employees, work environment [4, 48], satisfaction. Moreover, by preventing emergency events and limiting their consequences, maintenance is related to the safety of processes and people [43].

Because the maintenance processes in an enterprise depend on the context of the enterprise, its objectives, structure, internal constraints and external conditions, it is not possible to provide a standard formula for achieving sustainable development in terms of maintenance, given its complexity in various systems. Nevertheless, it is possible to clarify some of the common aspects of sustainable development in different industries and to indicate the general procedure to be followed when maintaining maintenance to the next level of sustainable maintenance. This procedure can be interpreted as an improvement cycle plan-do-check-act (P-D-C-A). In this way, the transition to sustainable maintenance is defined as a set of activities and processes that turn maintenance into sustainable one through the continuous process that consists of: (1) an assessment of current sustainability maintenance performance; (2) an identification of improvement areas; (3) a suggestion of specific actions across the company; and (4) an implementation of these actions. Therefore, the first step should be to assess the current maintenance performance from the perspective of the requirements of sustainable manufacturing.

Over the last twenty years, many measures and indicators, models and frameworks for measuring and monitoring the maintenance systems performance have been developed [23, 36]. Among them, the most popular assessment tool is the scorecard, in particular the balanced scorecard (BSC) by Kaplan and Norton [26]. BSC is a holistic approach that transfers the company's strategy (or strategy for any function in the enterprise) to clearly predefined goals related to four different perspectives, namely: financial, clients, internal processes, and learning and development. This diversity of perspectives is important for the measurement of performance because intangible assets, such as customer relations, employee skills, knowledge and innovations, are currently treated as the main source of competitive advantage for enterprises. Balanced scorecard clearly transfers focus from current financial results to building or strengthening internal potential and investing in people, systems, procedures and internal processes in order to improve future achievements. Kaplan and Norton also pointed out that the four perspectives presented in the overall concept are just an example and may change depending on the purpose of the assessment. Hence, it is possible to add perspectives and change their names. This approach was used to design models for assessment of maintenance performance [2, 9, 11, 12, 31, 34, 41, 47, 54]. The literature review of models of maintenance assessment based on the Kaplan and Norton's scorecard shows that: (1) every author has a unique way to classify maintenance assessment perspectives. The different categories of perspectives show different areas of interest in maintenance performance. They also differ in their choice of criteria describing each perspective; (2) some categories of perspectives and criteria are recognized by all authors as vital for management of the maintenance function, for example, much emphasis has been placed on maintenance cost-related measures, skills and competencies of maintenance workers, safety and environment, maintenance work management, and customer satisfaction.

However, in any of the literature models, according to the authors (the model developed by [47] is an exception), criteria important from sustainable manufacturing perspective, such as waste requirements, energy consumption, water, consumables, work environment etc., were not taken into account comprehensively. Although the model developed by [47] should be considered pioneering in the assessment of maintenance sustainability, further research is needed, in particular with regard to how to assess and use the assessment results for improvement purposes.

3. The framework of maintenance sustainability performance assessment

3.1. Assumptions, goal and scope of assessment

Considering [35, 40] it was assumed that 'maintenance as a subsystem of the manufacturing system is sustainable if it contributes to the sustainability of the large system (of which it is a part) while maintaining its own sustainability'. This definition results in an important implication for the design of the maintenance assessment model from the perspective of sustainable manufacturing. The model should simultaneously include two elements, firstly the assessment of results in relation to the superior system represented by, for example, stakeholders and their requirements, secondly, the maintenance potential. Moreover, because the recipients of the result of the assessment are decision-makers, the use of too many indicators and measures could lead to the 'dilution' of the information they contain. Therefore, it is necessary to design a composite indicator to assess sustainable maintenance. Composite indicators are used in many areas of research, including maintenance e.g. [13, 20].

Considering the above, it was assumed that the concept of maintenance sustainability assessment should fulfil the following criteria: (1) it should integrate the three factors of sustainability – economic, environmental and social, (2) it should take into account the links between maintenance and its stakeholders, (3) it should be based on financial and non-financial measures, (4) it should be easy to interpret, as the composite maintenance performance is a model in the mathematical sense. The first three requirements refer to the criteria being assessed, while the fourth requirement concerns the method of presenting the result of the assessment.

One of the methods of developing performance measurement models most frequently mentioned in the literature from the perspective of sustainable development, which: (1) combines the strategy with the objectives and measures of their implementation, (2) includes and links financial and non-financial measures, (3) takes into account the links between internal effectiveness of processes and their external efficiency, and in addition (4) enables inclusion of dimensions of sustainable development, is a scorecard developed by Kaplan and Norton. This method is also used by many authors to develop models for assessment of maintenance performance (see chapter 2). However, it has not yet been applied to a comprehensive assessment of maintenance performance from the perspective of sustainable manufacturing requirements. Considering the above, the general framework of the developed model for measuring maintenance performance from the perspective of sustainable manufacturing was embedded in the general assumptions of the balanced scorecard.

The goal of the of maintenance sustainability assessment is to provide information on current maintenance performance and support decision-makers in the decision-making process regarding future directions of operations. This information should be synthetic, and thus show the result of the assessment in an aggregated way, and at the same time enable decomposition to lower levels showing the impact of each of the assessed criteria to the final result. However, the BSC method does not include any techniques for quantifying the contribution of each perspective, or criteria/indicators within the same perspective. The developed concept of assessment of maintenance from the perspective of sustainable manufacturing solves this problem based on the paradigm of aggregate assessment. The general scheme of the methodology for aggregate maintenance assessment includes three main stages: (1) Assessment criteria selection, (2) Selection of methods of criteria assessment, and (3) Development of Composite Maintenance Sustainability Index.

The model of maintenance performance assessment from sustainable manufacturing perspective developed according to the three stages scheme should help the maintenance managers transfer the strategy into action and offer predictive measures for future performance. In particular, it should answer the four important questions: (1) What is the impact of the perspectives and criteria on the sustainable maintenance performance? (2) How can importance of these perspectives and criteria be determined? (3) How can maintenance performance be measured? (4) What is the actual level of maintenance performance from sustainable manufacturing point of view?

3.2. Identification of assessment criteria

Initial four classic perspectives of the BSC model suggested by [26] were modified (e.g. as suggested by [39] the customer perspective was replaced by the stakeholders' perspective), criteria for the assessment of each perspective and the corresponding specific issues were defined, thus extending the traditional BSC model to the hierarchical structure of HBSC (Fig. 1).

To ensure relevance and credibility of the developed model of measurement of maintenance performance and the corresponding criteria, two types of information sources were used. First of all, on the basis of the literature analysis, the assessment criteria and detailed issues for each of the criteria were distinguished. Secondly, experts were consulted (researchers and practitioners from enterprises). Experts representing the scientific community assessed completeness and indicated potential gaps in the model. On the other hand, experts representing business practice, apart from completeness, assessed the scope, usefulness and the possibility of conducting an assessment in real business conditions.

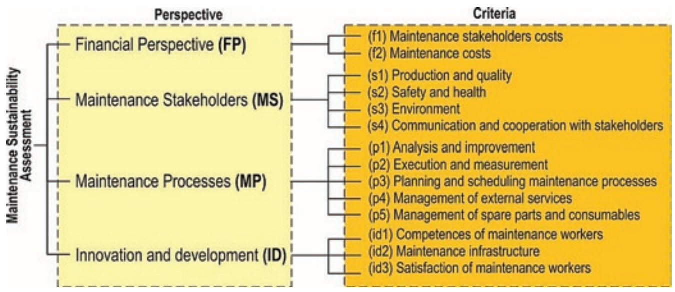


Fig. 1. Hierarchical model for maintenance sustainability assessment

The first of the perspectives in the assessment model is the 'Financial Perspective' (FP). It reflects the maintenance function that can be defined as ensuring human and equipment safety, respect for the environment and accessibility at the lowest possible cost. The assessment of this perspective includes two criteria: (f1) costs of maintenance stakeholders and (f2) maintenance costs. The second perspective is the perspective of 'Maintenance Stakeholders' (MS). Maintenance stakeholders are various organizational units of the company that receive services, in particular the production department and its employees. The key aspects of this perspective include, among others: satisfaction with services rendered, response time, availability of technical equipment, information obtained from technical support services, cooperation between departments and the safety of employees and the environment. Under this perspective, four criteria will be assessed: (s1) production and quality, (s2) safety and health, (s3) environment, (s4)

Table 1. Criteria of sustainable maintenance assessment

Perspective	Criterion	Description
Financial	f1	costs related to production downtime, quality discrepancies associated with failures / unstable machinery operation, unplanned costs of purchase of spare parts and sub-contractors services, costs of non-compliance with environmental legal requirements, environmental costs due to malfunctions (e.g. waste treatment, penalties), costs of disposal of wastes generated during service work, overtime costs, costs of non-compliance with work safety requirements, costs related to injuries and accidents of maintenance workers, operators and third parties that occurred during maintenance works, as a result of failures, etc.,
	f2	principles of determining the budget of the maintenance department, costs of labor, training, purchase and maintenance of inventory of spare parts and consumables, cost of sub-contractors, cost of media consumed by maintenance department (electricity, compressed air, water)
Maintenance stakeholders'	s1	availability and reliability of machines, response to the request for service, quality of training provided by maintenance department for production employees, availability and quality of procedures and instructions for operators, machines capability, product non-compliance due to unstable machine operation and failures
	s2	injuries and accidents while performing maintenance work by operators, sub-contractors and abandonment or non-performance of such work resulting from them, system for identification of non-compliance with OHS principles, improvement actions undertaken by maintenance staff to eliminate health and safety hazards, limiting criticality of accidents/ failures
	s3	environmental incidents during works performed by operators, sub-contractors and resulting from the abandonment or non-performance of such works, waste monitoring system related to them, product waste caused by unstable machinery and failures, improvement actions taken by maintenance staff to eliminate environmental hazards related to machinery failures, limiting criticality of accidents/ failures
	s4	communication channels used (e.g. mobile technologies, use of CMMS system), formal system of meetings, incompatibilities caused by lack of communication or untimely transfer of information, work of multidisciplinary teams to solve problems and improve
Maintenance processes'	p1	analysis of: technological limits of media consumption by machines (e.g. water, electricity), emergency events and their causes, repair time, delays in task execution, analysis of consumption of lubricants, hazardous substances used during servicing, formal improvement system and its effectiveness, modernization of machines and devices and their effectiveness, actions aimed at extending the life cycle of lubricants, and limiting the consumption of hazardous substances
	p2	the level of execution of the plan and schedule of maintenance, the method and scope of recording and documenting maintenance work (record standards), inspection system: e.g. noise, leakage or emission level, waste generated during maintenance works, their toxicity, waste segregation procedures, environmental incidents occurring during maintenance work, injuries and accidents concerning maintenance staff during service performance, compliance with applicable OHS procedures
	p3	availability of data and information on operational events, maintenance performed and their effectiveness, availability of information from diagnostic tests, formal methods and criteria for identifying critical equipment (including safety and environmental issues in machine criticality assessment), criteria for selection of maintenance strategies for individual machines and devices, procedures and work instructions that take into account OSH and environmental hazards
	p4	methods and criteria for selection of sub-contractors, defining the scope of services, cooperation rules and procedures (including, for example, safety rules, waste management procedures), how to document the activities completed, monitoring the execution
	p5	methods and criteria implemented for selection and assessment of suppliers of spare parts and consumables, demand planning, inventory monitoring, use of environmentally friendly consumables, storage methods (safety and environmental requirements), use of regenerated/remanufactured parts
Innovation and development	id1	planning of training for employees, new employee introducing programs, methods for verifying knowledge and skills of employees, training topics (e.g. improvement methods and techniques, new technologies, environmental management and OSH issues)
	id2	adequacy of quality and quantity of equipment in relation to the scope of performed maintenance works, including diagnostic tests, planning and implementation of investments in this area, delays in service work resulting from lack of availability or quality of equipment, the scope of IT tools for planning, supervising, monitoring and analysis work of technical facilities and maintenance processes,
	id3	working hours, working environment, rotation of maintenance staff, motivation systems

communication and cooperation with stakeholders. Another perspective (third) is 'Maintenance Processes' (MP) which concerns all aspects related to maintenance operations, including planning and scheduling, monitoring and control as well as improvement. The overall objective is to ensure efficiency and effectiveness of operations, through proper organization of maintenance work, improvement of spare parts and consumables management, improvement of service reliability by own technical services and external units (service providers), improvement of safety of services provided, etc. Within this perspective, five criteria are to be assessed: (p1) analysis and improvement, (p2) execution and measurement, (p3) planning and scheduling maintenance processes, (p4) management of external services, (p5) management of spare parts and consumables. The fourth perspective, 'Innovation and development' (ID), indicates that achieving efficiency from the financial, stakeholders and internal processes perspectives depends to a large extent on the competencies of employees, resources that they can have during the implementation of tasks and the level of job satisfaction. Within this perspective, three areas are assessed: (id1) competences of maintenance workers, (id2) maintenance infrastructure, (id3) satisfaction of maintenance workers. The detailed scopes of each criterion of assessment are presented in the table 1.

The scope of the assessment of individual criteria presented in Table 1 in authors' opinion covers all the key maintenance issues from the perspective of sustainable manufacturing. Each of the issues describing a specific criterion will be assessed with a point scale by a team of experts from the company, and the final assessment of the criterion will be calculated as the ratio of the number of points obtained to total number of points available. Due to the scope of the article, a detailed description of the method of criteria assessment has not been presented. The presented model (Fig. 1 and table 1) is designed for the company's internal purposes. It can be implemented as a self-assessment tool and at the same time a 'road map' of activities that should be considered when striving for improvement. The model does not impose or suggest ready-made solutions but presents many approaches to achieving success in meeting the challenges of sustainable manufacturing.

3.3. Structure of the composite index

One of the assumptions of the assessment of maintenance sustainability is the scheme of presentation of the result of the assessment. This result is to be presented in the form of an interpretation-friendly composite index, i.e. it is a function in the mathematical sense and at the same time it needs to present the contribution of each of the perspectives and assessment criteria to the final result of the assessment. Based on the literature review [8, 16, 18, 53] to solve the problem of aggregating perspectives and criteria that are interdependent, a non-additive fuzzy integral was selected. Fuzzy integral method applies fuzzy measures to deal with the problems of human subjective perception and uncertainty as well as to address the level of interdependency effects among criteria [51]. Fuzzy measure is non-additive hence the total importance of individual features may not be equal to the combined importance of the features. In this research, we are motivated to implement the theory of fuzzy measures to model the importance and interaction between features in the Choquet integral

The principle and construction process of the non-additive fuzzy integral for composite maintenance sustainability index (CMSI) can be described in three steps: (1) Determine the importance of decision criteria with linguistic variables; (2) Determine the decision factors importance using fuzzy measure; (3) Calculate the aggregate value (CMSI).

Step 1. *Determine the importance of decision criteria with linguistic variables_*

The first step in developing a maintenance sustainability index focuses on weighting the individual elements (perspectives and criteria). Weighting is to assign importance for each element based on their relative importance. It is a very sensitive process which can lead to different results due to different importance assigned. Therefore, it affects the accuracy of the assessment. The determination of the importance of each of the perspectives and assessment criteria is carried out by a team of experts. Because, experts have different levels of cognitive vagueness (different experience and knowledge), linguistic variables are used to determine the importance degree of maintenance assessment perspectives and criteria. Those importance weights are aggregated by applying the fuzzy arithmetic. During construction of CMSI FN-OWA (Fuzzy Number Ordered Weighted Average) [7] aggregation operator was applied. The main reason why FN-OWA was selected is that it has ability to aggregate not only the quantitative data, but it also can handle linguistic as well as crisp data. Moreover, it is idempotent operator which means that operator retains the same linguistic state if all input criteria have equal values [45]. The aggregated fuzzy importance weights of decision factors need to be converted into crisp numbers for subsequent utilization in fuzzy measure construction.

Step 2. *Determine the decision factors weight using fuzzy measure*

One important issue in sustainable assessment is the need to express not only the importance of individual features but also interactions between them. There are normally three kinds of interactions between two criteria A and B (μ denotes importance/weight)

a) Synergetic interaction, which can be represented by $\mu(A \cup B) > \mu(A) + \mu(B)$,
b) Inhibitory interaction, which can be represented by $\mu(A \cup B) < \mu(A) + \mu(B)$,
c) Non-interaction, which can be represented by $\mu(A \cup B) = \mu(A) + \mu(B)$.

Classical probability theory can only be applied to the third situation when there is no interaction between two criteria, while fuzzy measure theory can describe any of the three situations [16]. The fuzzy measure is a measure for representing the membership degree (importance) of an object (a criterion) in candidate sets (set of criteria). Fuzzy measures can be considered as the generalization of the probability measure. In this case, the additive property is replaced with a weaker requirement. Mathematically, a fuzzy measure is defined as follows [17]:

Definition 1

A discrete fuzzy measure on X is a set function $\mu: 2^X \to [0,1]$ satisfying:

1. $\mu(\emptyset)=0$, $\mu(X)=1$,
2. $A \subset B$ implies that $\mu(A) \le \mu(B)$ (monotonicity).

However, constructing suitable fuzzy measure is not trivial; because the number of coefficients increases exponentially as the number of features grows (in general such measure requires $2^{|X|}$ values to be defined). Moreover, fuzzy measures also need to meet the monotonicity and continuity requirements. To address this problem Sugeno [50] proposed the λ-measure (also called Sugeno measure, or λ-addtive measure). To restrict number of required coefficients Sugeno added additional axiom to fuzzy measure definition:

Definition 2 (Discrete Sugeno λ-measure):

A discrete fuzzy measure is called Sugeno λ-measure if it satisfies:

3. If $A \cap B = \emptyset$, then $\mu_\lambda(A \cup B) = \mu_\lambda(A) + \mu_\lambda(B) + \lambda\mu_\lambda(A)\mu_\lambda(B)$.

Sugeno [50] proved that given those 3 axioms, fuzzy measure can be uniquely determined using only $n = |X|$ coefficients μ_i that are often called fuzzy densities that represent the degree of importance of criteria i-th and can be calculated by parametric or nonparametric methods. The λ-measure can be calculated using following formula:

$$\mu_\lambda(A) = \frac{1}{\lambda}\left[\prod_{x_i \in A}(1+\lambda\mu_i) - 1\right] \quad (1)$$

where $\lambda > -1$ is solely determined by the equation:

$$\lambda + 1 = \prod_{i=1}^{|X|}\left(\lambda\mu_i + 1\right) \quad (2)$$

λ-measure is constrained by a parameter λ, which describes the degree of additivity the attributes hold. According to [21, 22]:

- If $\lambda < 0$, then it implies that the attributes are sharing sub-additive (redundancy) effect.
- If $\lambda > 0$, then it interprets that the attributes are sharing super-additive (synergy) effect.
- If $\lambda = 0$, then it indicates that the attributes are non-interactive.

It is important to note that in fuzzy measure importance of the single criterion or a pair of criteria it not solely determined by $\mu(\{x_i\})$ or $\mu(\{x_i,x_j\})$. One need to consider all $\mu(A)$ such that $x_i \in A$ or $\{x_i,x_j\} \subseteq A$. Murofushi et al. [37, 38] proposed solution to this problem based on game theory for single criterion and utility theory for pairs for criteria. Based on fuzzy measure, the importance index (Shapley value) and interaction indices of different perspectives and criteria were defined.

Definition 3 (Shapley importance index, Shapley value) [37]:

Let μ be a fuzzy measure on X. The Shapley value (or the importance index) for every element $x_i \in X$ is defined by following formula:

$$\Lambda(x_i) = \sum_{A \subset X-\{x_i\}} \gamma_X(A)\left[\mu(A \cup \{x_i\}) - \mu(A)\right], \qquad (3)$$

where:

$$\gamma_X(A) = \frac{(|X|-|A|-1)!|A|!}{|X|!}. \qquad (4)$$

The Shapley value with respect to the measure μ is a vector $v = [\Lambda(x_1), \Lambda(x_2), \ldots, \Lambda(x_n)]$. It describes the global importance of every element by taking into account the effects of all subsets with and without the given element. According to the definition, the Shapley value has the property that the sum of all its components is '1', which can be formulated as $\sum_{i=1}^{n}\Lambda(x_i) = 1$. Scaled by a factor n, Shapley values greater than '1' indicate that the given element (criterion) is more important than the average.

Another important topic is the notion of interaction among two criteria, as proposed by [38].

Definition 4 (Interaction Index) [38]:

Let μ be a fuzzy measure on X. Interaction index of criteria x_i and x_j is defined by:

$$I_\mu(x_i,x_j) = \sum_{A \subset X-\{x_j,x_j\}} \xi_X(A) I_\mu(x_i,x_j \mid A), \qquad (5)$$

where:

$$\xi_X = \frac{(|X|-|A|-2)!\,|A|!}{(|X|-1)!}, \qquad (6)$$

and

$$I_\mu(x_i,x_j|A) = \mu(A \cup \{x_i,x_j\}) - \mu(A \cup \{x_i\}) - \mu(A \cup \{x_j\}) + \mu(A). \quad (7)$$

Interaction index takes values from $[-1,1]$ interval, where negative (positive) values indicate negative (positive, synergic) interaction.

Based on the concept of Shapley importance index and interaction index, the contribution of one or more elements to a whole fuzzy measure can be described as follows:

a) Element x_i is said to be more important than x_j if the Shapley value $\Lambda(x_i) > \Lambda(x_j)$;

b) Elements x_i and x_j are redundant if the interaction index $I_\mu(x_i,x_j) < 0$;

c) Elements x_i and x_j are complementary if the interaction index $I_\mu(x_i,x_j) > 0$

When fuzzy measure is constructed the next step is to apply it in Choquet integral to obtain value of CMSI.

Step 3. *Calculate the aggregate value (CMSI).*

The fuzzy integral is used in the sustainable maintenance assessment to combine assessments primarily because this model does not need to assume independence among the criteria. A formal definition of the Choquet integral is as follows:

Definition 5 (Discrete Choquet integral):

Let μ be a fuzzy measure on X. Choquet integral of function $f: X \to [0,1]$ with respect to fuzzy measure μ is defined by:

$$C_\mu(f_1, f_2, \cdots, f_n) = \sum_{i=1}^{n}\left(f_{(i)} - f_{(i-1)}\right)\mu\left(A_{(i)}\right), \qquad (8)$$

where $f_{(i)}$ indicates that the indices have been permutated so that $0 \le f_{(1)} \le \cdots \le f_{(n)} \le 1$, $A_{(i)} = \{x_{(i)}, \cdots, x_{(n)}\}$ and $f_i = f(x_i)$.

Main properties of Choquet integral important from perspective of multi-criteria decision making, are [16, 19]: idempotence, continuity, monotonicity (non-decreasingness) with respect to each argument, stability under the same positive linear transformation. Because of stability of Choquet integral, the exact numerical scale in relation to which the calculations are made is not important. This significantly simplifies the collection of data from experts, enabling the assessment on a linguistic scale without the need to establish specific interpretations. However, the interest in the fuzzy integral is mainly due to its ability to represent the interactions between criteria. This is due to the fact that weights in fuzzy measure are assigned to every subset of all criteria. The above properties show that fuzzy integrals have the potential for sustainability maintenance assessment.

Calculation procedure of Composite Maintenance Sustainability Index (CMSI) requires fuzzy measure (μ) and actual values of criteria obtained from company assessment team (h). The outline of this procedure is given on Fig. 2.

CMSI value measures organization's maintenance sustainability and lie in the range between 0 and 1. Value of CMSI closer to '0' indicates that the maintenance is unsustainable; whereas a value closer to '1', means that the maintenance structure is sustainable and contributes to the sustainability of the manufacturing system while maintaining its own sustainability.

4. Empirical studies of the importance of perspectives and criteria assessment for assessing maintenance sustainability performance

The determination of the importance of both perspectives and individual criteria was carried out by an expert method according to the scheme: (1) developing linguistic scale; (2) appointing experts; (3) assessment of importance of perspectives and criteria by experts; (4) calculating the average value for perspectives and criteria; (5) developing λ measure; (6) determining the importance and interactions between perspectives and criteria. In the assessment model, linguistic variables represent a subjective assessment of the importance of the perspectives, as well as their criteria. A five-level linguistic scale was used (Table 2). Only descriptive definitions of extreme elements of the scale were presented, i.e.: irrelevant - the perspective/criterion is

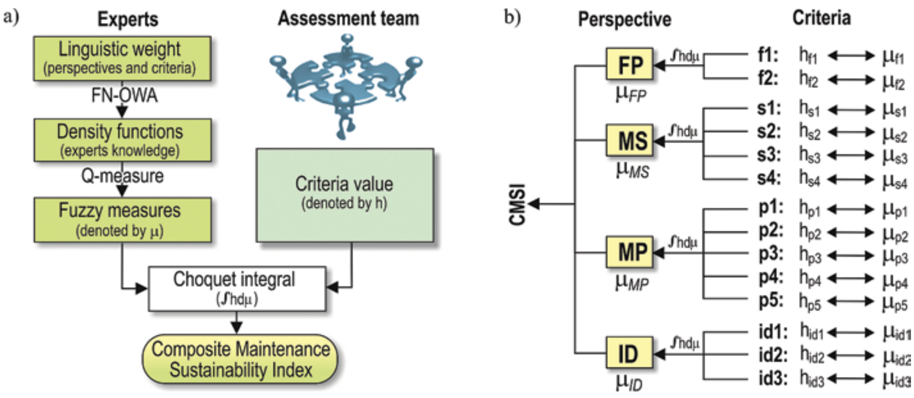
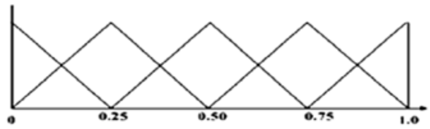


Fig. 2. Calculation procedure of Composite Maintenance Sustainability Index (CMSI). Outline of CMSI construction process. (b) Scheme of actual hierarchical calculation of CMSI value

Table 2. Linguistic scales

Linguistic terms	Linguistic values	Triangular fuzzy membership functions
Very important	(0.75, 1.0, 1.0)	
Important	(0.5, 0.75, 1.0)	
Moderately important	(0.25, 0.5, 0.75)	
Equal important	(0, 0.25, 0.5)	
Irrelevant	(0, 0, 0.25)	

almost irrelevant to the level assessment; very important - the perspective/criterion can be used alone to assess the entire level.

Based on the model developed (fig. 1) and the adopted scale of linguistic assessments, a form was designed for the experts to determine the importance of perspectives and criteria. The questionnaire contained the definition and meaning of each of the perspectives. After the questionnaire was designed, it was distributed among 3 experts from enterprises to verify the wording, its intelligibility and unambiguity.

In order to determine the importance of perspectives and assessment criteria, empirical studies were carried out in production companies. For research purposes, companies that have sustainable development or corporate social responsibility policies defined and have implemented quality management system (e.g. ISO 9001, ISO 22000, BRC, IFS, ISO / TS 16949), are implementing or currently operating in accordance with the Lean Manufacturing concept and perform maintenance operations by themselves were selected. Eight companies from the automotive industry (A) and seven food industry enterprises (F) were invited to the research. The research was carried out among the heads of maintenance departments and heads of production separately in each of the companies.

The assessment of importance of perspectives and criteria was carried out individually in each of the companies during meetings with the head of the production department and the head of the maintenance department, at which the model of sustainable maintenance assessment was described at the outset, and then the principles for assessing individual perspectives and criteria were presented. Experts (heads of Maintenance department (M) and heads of Production department (P)) were requested to assess the importance of perspectives and criteria depending on the hierarchical system using the five linguistic variables. The experts were not limited with the imposed numerical interpretation of the applied linguistic variables.

The average importance for each perspective was calculated using FN-OWA operator with weight vector that discards extreme values. Input values were arranged with respect to natural order of linguistic terms (irrelevant < less important < moderately important < important < very important). The same method was used to aggregate expert assessments for criteria inside perspectives (second level criteria). The last step was to calculate the single numerical values for each of the fuzzy numbers. These values can be treated as an average assessment of the importance of individual perspectives/criteria. Application of Center of Gravity defuzzification method led to the results presented in Table 3 and 4.

Calculated values of μ_i (Table 3 and 4) were used to develop fuzzy measure. Algorithm presented in [33] was implemented in R 3.4.4 Statistical Computing Platform and applied without fixing λ to averaged importance values to construct Sugeno λ-measure (Definition 2). The main benefit of this procedure is its ability to automatically rescale input values so that obtained measure optimally reproduces expert data. Obtained measures as well as λ-values for automotive industry and food industry are presented in Table 5.

Table 3. Fuzzy densities μ_i obtained by experts for perspective

Perspective	Automotive industry (A)			Food industry (F)		
	MA	PA	MA &PA	MF	PF	MF &PF
FP	0.2917	0.3333	0.3173	0.2500	0.2500	0.2500
MS	0.3542	0.3750	0.3558	0.3750	0.3750	0.3750
MP	0.3333	0.3125	0.3173	0.3500	0.3500	0.3438
ID	0.2292	0.2083	0.2115	0.2500	0.1750	0.2187

Table 4. Fuzzy densities μ_i obtained by experts for criteria

Perspective	Criteria	Automotive industry (A)			Food industry (F)		
		MA	PA	MA &PA	MF	PF	MF &PF
FP	f1	0.3608	0.4165	0.3972	0.3998	0.3998	0.4026
	f2	0.3887	0.2495	0.3330	0.3330	0.2328	0.29132
MS	s1	0.2833	0.3000	0.2923	0.3000	0.3000	0.3000
	s2	0.3000	0.2833	0.2923	0.2200	0.3000	0.2583
	s3	0.2167	0.2000	0.2154	0.2600	0.2000	0.2333
	s4	0.1833	0.1333	0.1615	0.1800	0.1400	0.1583
MP	p1	0.1800	0.1662	0.1726	0.1660	0.1494	0.1591
	p2	0.25000	0.2500	0.2500	0.2500	0.2500	0.2500
	p3	0.2220	0.2080	0.2112	0.1996	0.1828	0.1940
	p4	0.1940	0.1802	0.1855	0.2332	0.2332	0.2290
	p5	0.1660	0.1245	0.1468	0.1660	0.1162	0.1453
ID	id1	0.3333	0.3542	0.3365	0.3000	0.3000	0.3021
	id2	0.3333	0.2708	0.3077	0.3500	0.3000	0.3229
	id3	0.2708	0.2500	0.2692	0.2250	0.1250	0.1771

Table 5. Fuzzy measure λ value for criteria

Perspective	Criteria	Automotive industry (A)			Food industry (F)		
		λ_{MA}	λ_{PA}	$\lambda_{MA\ \&PA}$	λ_{MF}	λ_{PF}	$\lambda_{MF\ \&\ PF}$
FP	f1, f2	1,7862	3,2141	2,0394	2,0070	3,9474	2,6112
MS	s1, s2, s3, s4	0,0462	0,2622	0,1110	0,1150	0,1814	0,1468
MP	p1,p2,p3,p4,p5	-0,0296	0,2014	0,0896	-0,0365	0,1938	0,0593
ID	id1, d2, id3	0,2097	0,4743	0,3032	0,4762	1,5120	0,8855

Table 6. Interaction index for criteria

Perspective	Criteria	Automotive industry (A)			Food industry (F)		
		MA	PA	MA &PA	MF	PF	MF &PF
FP	f1, f2	0.2505	0.3340	0.2698	0.2672	0.3674	0.3062
MS	s1, s2	0.0040	0.0233	0.0097	0.0078	0.0168	0.0117
	s1, s3	0.0029	0.0166	0.0072	0.0092	0.0113	0.0106
	s1, s4	0.0030	0.0157	0.0072	0.0068	0.0113	0.0091
	s2, s3	0.0024	0.0112	0.0054	0.0064	0.0080	0.0072
	s2, s4	0.0026	0.0106	0.0054	0.0047	0.0080	0.0062
	s3, s4	0.0019	0.0075	0.0040	0.0055	0.0054	0.0056
MP	p1, p2,	-0.0013	0.0088	0.0040	-0.0015	0.0076	0.0024
	p1,p3	-0.0012	0.0074	0.0034	-0.0012	0.0056	0.0019
	p1,p4	-0.0016	0.0110	0.0048	-0.0018	0.0093	0.0029
	p1,p5	-0.0010	0.0064	0.0030	-0.0014	0.0071	0.0022
	p2,p3	-0.0014	0.0095	0.0043	-0.0021	0.0118	0.0034
	p2,p4	-0.0013	0.0080	0.0036	-0.0017	0.0087	0.0027
	p2,p5	-0.0009	0.0044	0.0023	-0.0010	0.0036	0.0014
	p3,p4	-0.0012	0.0066	0.0034	-0.0015	0.0059	0.0022
	p3,p5	-0.0011	0.0055	0.0029	-0.0012	0.0044	0.0017
	p4,p5	-0.0009	0.0048	0.0025	-0.0014	0.0056	0.0020
ID	id1, id2	0.0240	0.0482	0.0327	0.0527	0.1488	0.0931
	id1, id3	0.0196	0.0447	0.0287	0.0348	0.0695	0.0541
	id2, id3	0.0196	0.0348	0.0264	0.0402	0.0695	0.0574

Table 7. Shapley value for perspective

Perspec-tives	Automotive industry			Food industry		
	MA	PA	MA &PA	MF	PF	MF &PF
FP	0.9616	1.0880	1.0576	0.8040	0.8608	0.8320
MS	1.1836	1.2360	1.1952	1.2404	1.3184	1.2792
MP	1.1088	1.0152	1.0576	1.1512	1.2256	1.1652
ID	0.7460	0.6612	0.6900	0.8040	0.5952	0.7236

Once the fuzzy measures for perspectives and criteria are identified, the next step is to compute the interaction index using formula 5, 6 and 7 (Table 6.).

The interaction index allows to identify criteria that are synergistic (positive value of the indicator) or redundant (negative value of the indicator). According to the assessment of the managers of the maintenance departments of both industries (MA and MF assessment), the criteria describing the perspective of 'Maintenance processes' (MP) are redundant, which means that some criteria should be rejected (see also λ_{MA} and λ_{MF} in Table 5), however, according to other experts both the criteria describing this perspective and the criteria describing the remaining perspectives are synergistic. Nevertheless, since the values of interaction ratios are close to zero, it is difficult to draw binding conclusions. Therefore, only changes to the description of the criteria have been introduced without rejecting any of them. Nevertheless, the analysis presented above shows that in the assessment of importance of the criteria 1) the opinions of various groups of stakeholders should be considered, because the opinion of only one group may lead to wrong conclusions; 2) aggregated results of all stakeholder groups, as well as partial ones assigned individually to each stakeholder group should be presented, because they can provide information on potential directions of model improvement.

Once the fuzzy measures for perspectives and criteria are identified, and interaction index is computed the next step is to compute the Shapley value using formula 3 and 4 (Tab. 7 and 8). The goal is to determine relative importance between perspectives and between criteria.

The results presented in Table 7 indicate that regardless of the industry or department represented by experts, the most important is the 'Maintenance Stakeholders' (MS) perspective, and the 'Innovation and Development' (ID) perspective is the least important (Fig. 3a, 3b, 3c). Recognition of the MS as the most important perspective is understandable and results from the role played by maintenance in the enterprise. Analyzing the importance of the other two perspectives in most indications, the 'Maintenance processes' (MP) perspective is more important than the 'Financial perspective' (FP).

This means that the assumptions on the need to include non-financial criteria taken for the concept development are confirmed by the experts of both industries. Comparing the results of experts' assessment from the point of view of the industry (Fig. 3a), they are consistent only for extreme indications (the most important MS, the least important ID), while the other ones differ. In the food industry, the MP perspective is definitely more important than FP (compared to the automotive industry) in the opinion of both the heads of the maintenance department (Fig. 3b) and production managers (Fig. 3c). This difference may result from the specificity of the food industry. Inconsistencies caused by emergency events or incorrect performance of technical service affect the health safety of the food product, which may result, for example, in the disposal of the entire batch of the product, the need to carry out cleaning and disinfection of the machine, which is associated with a financial loss. Thus, assigning a higher importance

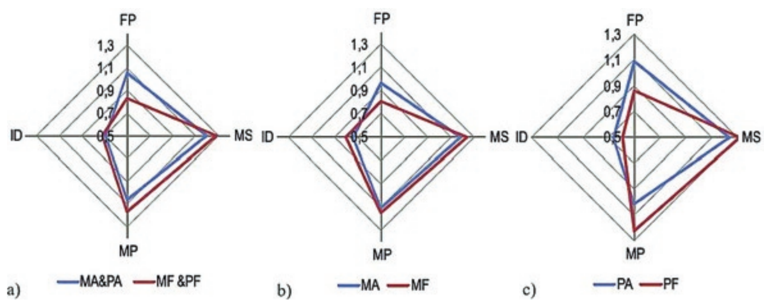


Fig. 3. Experts' perception of importance of perspectives

Table 8. Shapley value for criteria

Perspectives	Criteria	Automotive industry (A)			Food industry (F)		
		MA	PA	MA &PA	MF	PF	MF &PF
FP	f1	0.9722	1.1670	1.0642	1.0668	1.1670	1.1114
	f2	1.0278	0.8330	0.9358	0.9332	0.8330	0.8886
MS	s1	1.1516	1.3004	1.2132	1.2464	1.2716	1.2584
	s2	1.2192	1.2308	1.2132	0.9180	1.2716	1.0868
	s3	0.8820	0.8784	0.8980	1.0828	0.8552	0.9836
	s4	0.7468	0.5908	0.6756	0.7528	0.6020	0.6712
MP	p1	0.8890	0.8970	0.8945	0.8175	0.8060	0.8150
	p2	1.2360	1.3385	1.2910	1.2325	1.3355	1.2770
	p3	1.0970	1.1180	1.0925	0.9835	0.9825	0.9930
	p4	0.9585	0.9715	0.9605	1.1495	1.2475	1.1705
	p5	0.8195	0.6750	0.7615	0.8175	0.6285	0.7445
ID	id1	1.0647	1.1991	1.1004	1.0287	1.2147	1.1205
	id2	1.0647	0.9342	1.0104	1.1865	1.2147	1.1877
	id3	0.8706	0.8667	0.8892	0.7848	0.5706	0.6918

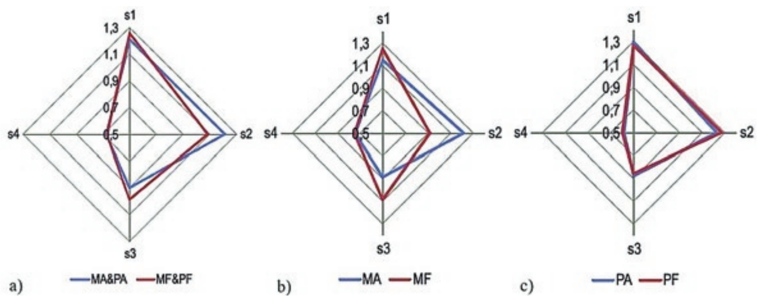


Fig. 4. Perception of importance of criteria from 'Maintenance Stakeholders' perspective

to the MP perspective is a kind of prevention against the increase of costs.

The results presented in Table 8 apply to the value of the Shapley index for the criteria describing particular perspectives. Analyzing the 'Financial perspective' (FP), all experts except the heads of the automotive industry maintenance department (MA) indicate that 'The costs of maintenance stakeholders - f1' is more important than 'maintenance costs - f2'. However, regardless of the industry (MA&PA and MF&PF), criterion f1 is more important than f2.

Assessing the perspective of 'Maintenance Stakeholders' (MS) (Fig. 4a), experts from both industries indicated that the first two criteria ('Production and quality - s1' and 'Safety and health - s2') are most important, followed by 'Environment - s3 'and' Communication and cooperation with stakeholders - s4 '. The assessments of experts

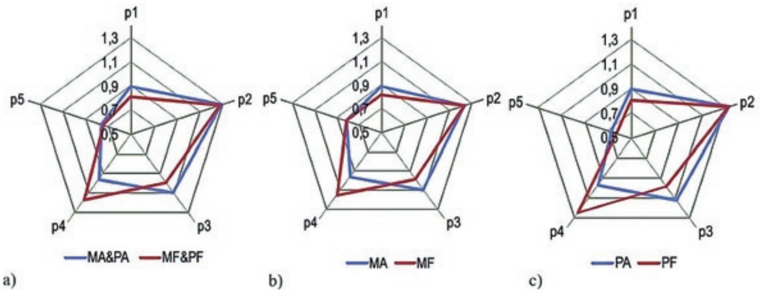


Fig. 5. Perception of importance of criteria from 'Maintenance Processes' perspective

representing production departments in both industries do not show any difference in preferences (Fig. 4c), while the differences are recognizable in the assessment of experts representing maintenance departments (Fig. 4b) and concern s2 and s3 criteria. According to MF experts, the criterion 'Environment - s3' is more important than 'Safety and health - s2', which may be related to the perception of the impact of emergency events primarily on the product (e.g. product disposal and related environmental impact).

Another perspective analyzed is 'Maintenance processes' (MP). The distribution of the importance of the assessment criteria in this perspective indicates (Fig. 5a) that the most important is the criterion 'Execution and measurement - p2', while the least important is the criterion 'Management of spare parts and consumables - p5'. For experts in both industries (Fig. 5a), the criterion of 'Management of external service - p4' is more important than 'Management of spare parts and consumables - p5'. This may indicate an increasing participation of third parties in the execution of maintenance work, as well as the transfer of responsibility for maintaining spare parts stocks. In the food industry (MF & PF (Fig. 5a), MF (Fig. 5b), PF (Fig. 5c)), this is the second, after the most important criterion 'Execution and measurement - p2'.

The fourth perspective is 'Innovation and development' (ID). According to the assessment of experts from the automotive industry (MA & PA) the most important criterion is 'Competence of maintenance workers - id1', while according to experts in the food industry (MF & PF) the most important criterion is 'Maintenance infrastructure - id2' (Table 8). Such a difference in perception of criteria importance may result from the production process and the product. The repeatable continuous production was the prevailing solution in companies representing the food industry. Hence, the use of, for example, technical diagnostic tools, their availability and quality is particularly important for the prevention of failures. Moreover, taking into account the assessment of food industry experts for the perspective (MP), where criterion (p4) is more important than (p5), indication that (id2) is more important than (id1) would be justified.

5. Conclusion

To change the conventional vision of maintenance as a cost generator, it is necessary to integrate sustainable perspective in maintenance decision-making process. This requires including economic, environmental and social sustainability requirements in the maintenance management system in order to reduce maintenance-related impacts and their consequences and develop a new system for assessing maintenance performance taking into account this impact and its consequences. According to these challenges, in this paper the authors present an original model for maintenance sustainability assessment to integrate the sustainability-related aspects into the conventional maintenance management.

The internal multidimensional complexity of sustainable maintenance resulting both from the context of the enterprise and its objectives as well as from the scope of the impact of the maintenance processes implemented, makes it very difficult to assess maintenance activities in the context of sustainable production requirements. What is needed is both a synthetic evaluation of the entire maintenance area and individual aspects of its operation, so that it is possible to assess both the overall progress in performance and indicate areas for improvement. The presented assessment method meets these requirements. In addition, implementation of the assessment model will provide a systematic and gradual approach to structuring information (from whom, what, when, ...) that will enable policy makers to deal with the complexity of maintenance problems.

The model extends recent research work on Maintenance Performance Measurement by introducing the requirements of the sustainable manufacturing concept as the basis for performance measurement. Moreover, the model incorporates fuzzy integrals with fuzzy measure methodologies as the basis for construction CSMI. Fuzzy integral method applies fuzzy measures to deal with the problems of human subjective perception and uncertainty as well as to address the level of interdependency effects among criteria. To the best of the author's knowledge, such a framework of maintenance sustainability assessment is missing in previous studies.

When developing performance measurement models, the important issue is whether the presented model is universal and independent of the industry in which the company operates. The second part of the article presents preliminary results of the research on perception of importance of perspectives and criteria for assessing sustainable maintenance performance among experts from two industries. Results obtained from pilot studies show that in order to obtain reliable results, the research must be carried among representatives of different areas, not only heads of maintenance departments. Moreover, they indicate that industry conditions affect the perception of importance of assessment criteria, and thus the assessment model should be customized to the industry specifics.

Of course, there are several limitations to the research conducted and presented above, which require in-depth analysis and indicate directions for further research. First of all, the research was conducted on an expert sample represented by two industries. A larger sample would allow for more sophisticated assessment analysis of the importance and interactions between the assessment perspectives and the criteria describing them. It would be advisable to carry out research also in other industries and to include other company's functions in the research, for example, the HSE departments. Secondly, to provide more objective information on the applicability of the developed assessment model, further research should be carried out, using case studies of specific companies, thus confirming the practicality of the assessment procedure. Finally, because the CMSI calculation procedure is mathematically complex, which limits its application in practice, the intention of the authors is also to build an IT tool in the future. This tool would allow on the basis of an assessment of the criteria carried out by the evaluation team from the company to automatically generate CMSI value, and simultaneously through the built-in analytical module it would be possible to develop scenarios and assess their impact on the CMSI value, and thus identify directions for improvement.

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