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DIGITALIZATION POSITIVELY ASSOCIATES WITH THE ADOPTION OF SUSTAINABILITY PERFORMANCE METRICS IN MAINTENANCE PRACTICE: PRELIMINARY STUDY FINDINGS

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Abstract
The study investigates the relationship between digitalization and sustainability in maintenance decision-making. The analysis relies on raw and coded data from a questionnaire-based survey targeting manufacturing companies in the Republic of Serbia. Our findings suggest a strong positive association between digitalization and sustainability (Kendall's τ_b = 0.324, Z = 2.681, p = 0.007), demonstrating that digitalization plays a vital role in adopting sustainable maintenance performance metrics. In addition, factor analysis leveraging Multiple Correspondence Analysis suggests an association between technology, digitalization and maintenance of sustainable responsibility levels, providing additional evidence about digitalisation's role in adopting a sustainable maintenance approach.

Keywords*: sustainable maintenance, digitalization, multiple correspondence analysis, maintenance sustainable responsibility*

1. Introduction

The development of digital technologies and imposed sustainability initiatives (e.g., Green Deal) forced manufacturers to alter their business models. This forced many to turn their attention to maintenance in the hope of coping with these challenges, ultimately providing novel maintenance policies under the paradigm of SM (Sustainable Maintenance) (Campos & Simon, 2019; Franciosi et al., 2020).

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With the advent of Industry 4.0 (I4.0) solutions (e.g., Internet of Things), many consider that enabling technologies play a vital role in organisational performance (Todorovic et al., 2022), especially in switching to SM practices (Vasić et al., 2024). For instance, Karki & Porras (2021) argue that digitalization plays a crucial role in adopting SM by considering the optimization of both economic and sustainable factors. Similarly, Orošnjak et al. (2021) propose an EBM (Energy-Based Maintenance) concept covering both diagnosis/prognosis aspects, which can serve as an optimization solution as well. Other SM concepts emerged, such as Green Maintenance (Ajukumar & Gandhi, 2013), Energy-Oriented Maintenance (Xia et al., 2018), Sustainable Predictive Maintenance (Karuppiah et al., 2021), etc. However, although most on a theoretical basis, many had difficulties altering their maintenance practices, presumably due to low digitalization and technology capacities (Ahmed et al., 2023; Johansson et al., 2019).

As others started questioning the barriers and challenges in the adoption of SM, many agree that digitalization may play an essential role in the easier adoption of SM (Saihi et al., 2022; Sari et al., 2015). Therefore, this study attempts to test whether there is an association between digitalization and factors of sustainability in maintenance decision-making practices using a questionnaire-based approach. To do so, we perform dual analysis by testing independence and the relationship between these factors on one side and factor analysis to understand the association between these factors on the other.

The rest of the manuscript is structured as follows: The second section provides an in-depth description of the questionnaire-based survey items used for the study, including the description of the proposed statistical tests and factor analysis. The third section provides results and discusses preliminary findings. The last section provides concluding remarks, limitations, and implications of the work.

2. Methodology

2.1 Survey items used for the analysis

The survey items used comprise demographic information—company size (e.g., Small, Medium, large), industry sector, classification of primary activity, available standards, etc. Specifically, the survey data comprise the following items: *maintenance technology level? maintenance digitalization level? To what extent does your company care about environmental protection and sustainable responsibility? Does your company dispose of waste and recycle it? What existing sustainable maintenance performance metrics are being monitored?*

The first two items consider the ordinal (ranked) scale (1-low level; 7-high level) and digitalisation (1-does do not consider; 5-to a large extent). The multiple choice question explains the sustainable performance metric, but it is not fully provided due to paper length constraints. Please note that the raw data used for this study includes items related only to the proposed research questions. The survey instrument is constructed with many more items for measuring the level of sustainable maintenance readiness level and is available upon request. The targeted area is the Serbian manufacturing sector.

2.2 Coding of MSR levels

Delphi meetings are performed in person and online to code the variables. All three authors participated, and an interrater agreement was reached, relying on Cohen's kappa and Krippendorff's alpha. In the first round of coding, similar results are obtained for both Cohen's $\kappa = 0.916 \pm 0.055$ and Krippendorff's $\alpha = 0.916 \pm 0.048$ (Table 8). To ensure the replicability of coding, round 2 was performed with a 100% agreement score. The levels are coded as follows: MSR-L1 – Basic Sustainable Responsibility; MSR-L2 – Basic Sustainable Responsibility; MSR-L3 – Moderate Sustainable Responsibility; MSR-L4 – High Sustainable Responsibility; and MSR-L5, defined as Comprehensive Sustainable Responsibility.

Table 8: Interrater agreement of coders

Delphi	Coding	Kappa/Alpha	SE	$95\%CI_{Lower}$	$95\%CI_{Upper}$
R1	OM-KR*	0.916	0.068	0.740	1.000
R1	OM-NB*	0.874	0.042	0.876	1.000
R1	KR-NB*	0.916	0.057	0.804	1.000
R1	AVG_Cohen	0.916	0.055	0.806	1.000
R1	AVG_Krippendorff	0.916	0.048	0.817	1.000
R2	AVG_Cohen	1.000	0.000	1.000	1.000
R2	AVG_Krippendorff	1.000	0.000	1.000	1.000

*NOTE: *authors initials; AVG = Average of Cohen and Krippendorff scores. SE = Standard Error*

Specifically, the MSR-L1 considers one or more maintenance performance measures but only in one of the TBL dimensions, ignoring all others (e.g., ENV = energy consumption and CO_2 emissions). The MSR-L2 explains where a company considers a minimum of one item in two out of three TBL dimensions. For instance, an entity measures environmental (e.g., energy consumption) and social (e.g., health and safety) but ignores the economic dimension. The MSR-L3 explains the state where a company measures at least one item in all three dimensions but considers more than one item in only one dimension. The MSR-L4 suggests high sustainable responsibility with a minimum of two or more items in two dimensions. The MSR-L5 explains a fully sustainable, responsible maintenance function that measures at least two or more items in all three sustainability dimensions (e.g., social, environmental, and economic). The coded categories are then used to test the association with proposed items and for factor analysis.

Since our interest includes understanding the association between multiple variables, we perform coding of digitalization and technology items. Both items are coded as binary variables "low" if ranking (level) is ≤ 3, and "high" otherwise. All items are then used for factor analysis and visualisation leveraging MCA (Multiple Correspondence Analysis). The Chi-square distance metric is used. The explanation of individual variable contribution is given by variable inertia (variance). For hypothesis testing, we use Kendall's tau-b as a non-parametric correlation measure due to the items' ordinal (ranked) scale. The Chi-square statistic tests the association between other categorical (nominal) variables. Lastly, the diagnosticity of *p* values is performed using VS-MPR (Vovk-Sellke maximum *p*-Ratio) (Sellke et al., 2001), while corresponding test statistics report the relationship's strength.

3. Results & Discussion

3.1 Descriptive and inferential statistics

Firstly, we provide descriptive results of raw data (Figure 6). Most companies are within the process industry (82%) sector, where primary activity includes – manufacturing parts of vehicles (12%) and production of plastic packaging (10%), followed by others. Company sizes include large companies (43%), followed by medium (31%) and small (10%). The personnel filling out the survey are mostly Directors (19.6%), followed by Quality Managers (15.7%), Head of Maintenance (9.8%) and Head of Production (9.8%). Interestingly, 75% of companies have implemented the ISO 9001 standard, while 18% of companies do not carry out waste disposal tasks as part of their maintenance activities (e.g., oil treatment).

As for the survey items, 31% of companies claim that they take care of environmental protection and sustainability to a large extent, while 41% to a high extent. The technology level seems to follow a normal distribution, with most companies at the medium level (31%), suggesting a balanced approach, including some software solutions. Two companies reported that maintenance activities are performed manually without software solutions, and only two reported some technological and software solutions. Lastly, answering the question about digitalization's role, most companies report none to the minor (31%).

As for the MSR levels, most companies report MSR-L3 (27.4%), followed by MSR-L4 (21.6%) and MSR-L5 (19.6%). Only 7% of companies consider one TBL dimension (MSR-L1), while 17.6% consider at least two sustainable performance dimensions (e.g., environmental and economic aspects) in MDM (Maintenance Decision-Making). Given that digitalization and sustainability levels are reported as ordinal variables, we conduct Kendall's τ test statistic.

The results (Table 9) show a statistically significant positive association ($p < 0.05$) of reported variables. The correlation is highest between digitalization and technology level ($p < 0.001$, VS-MPR = 6122), followed by the technology and sustainability ($p < 0.001$, VS-MPR = 5308), and technology and MSR ($p < 0.001$, VS-MPR = 185). More importantly, there is a moderate correlation between digitalization and sustainability ($\tau = 0.398$, $p < 0.001$) and digitalization and MSR ($\tau = 0.324$, $p = 0.007$) with VS-MPR = 10.196, suggesting that there is 10 times more likely to find evidence under the alternative hypothesis that there is a positive association between digitalization and suggested MSR levels.

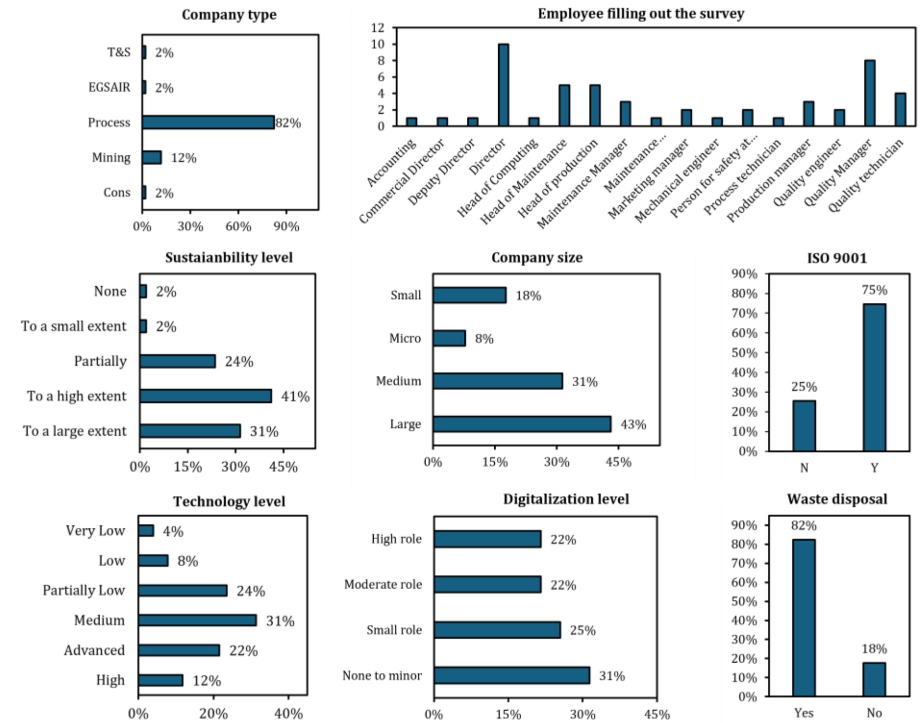

Figure 6: Descriptive results of demographics and selected survey raw data items

Table 9: Performed test statistics reported per Kendall's tau-b

Test Pairs	Statistic	Value	*Z*-score	*p*	VS-MPR
DIG – SUSRES	Kendall's τ_b	0.398	3.430	< 0.001	82.270
DIG – MSR-L	Kendall's τ_b	0.324	2.681	0.007	10.196
DIG – TECH	Kendall's τ_b	0.532	4.568	< 0.001	6122.012
TECH – SUSRES	Kendall's τ_b	0.540	4.536	< 0.001	5308.469
TECH – MSR-L	Kendall's τ_b	0.420	3.675	< 0.001	185.301

In addition, testing the association between variables using independence Chi-square statistic, all reported cases suggest the absence of independence and significant association between variables ($p < 0.05$). After comparing companies with ISO 9001 and the variables above, there is only a significant association between the items regarding waste disposal activities ($\chi^2 = 5.201$, $p = 0.023$). Thus, the reason for selecting Kendall's tau is that it provides both the strength and direction of the relationship, which is a Chi-square test limitation.

In sum, we confirm that there is strong evidence favouring the positive relationship between the level of digitalization and sustainability dimensions, specifically in sustainable responsibility and considering sustainable maintenance performance metrics in MDM. To gain deeper insight and understanding of the association between levels of MSR and included variables, dimensionality reduction and data visualization using MCA are performed.

3.2 Multiple Correspondence Analysis Results

The total inertia is $\Phi^2 = 1.750$ (Table 10), whereas the PC1 and PC2 account for 43%, while the first three PCs account for 59% of the total inertia. Note that the common practice is to use 70% of total inertia (Orošnjak & Šević, 2023)Hence, we additionally performed the analysis, which included four components. Ultimately, data did not suggest changes in association per the biplot projection of PC1 and PC2, which had sufficient inertia to understand the association between items. Thus, we rely on the first two components for discussion. (Note: Data and full MCA analysis can be provided to the reader per request.)

Table 10: The results of MCA representation of data and components

					PC1			***PC2***			***PC3***	
Name	***Q***	***m***	***λ***	***Cd***	***Co***	***Ctr***	***Cd***	***Co***	***Ctr***	***Cd***	***Co***	***Ctr***
MSR_L1	0.69	0.03	0.12	0.94	0.14	0.07	-1.23	0.24	0.18	1.40	0.31	0.25
MSR_L2	0.05	0.04	0.12	0.44	0.04	0.02	0.13	0.00	0.00	0.13	0.00	0.00
MSR_L3	0.73	0.07	0.10	0.33	0.04	0.02	-0.14	0.01	0.00	-1.34	0.68	0.46
MSR_L4	0.67	0.05	0.11	-0.02	0.00	0.00	1.48	0.60	0.40	0.48	0.06	0.05
MSR_L5	0.68	0.05	0.12	-1.50	0.55	0.24	-0.70	0.12	0.08	0.25	0.02	0.01
Low_Dig	0.69	0.20	0.03	0.37	0.49	0.06	0.24	0.20	0.04	0.00	0.00	0.00
High_Dig	0.69	0.05	0.11	-1.34	0.49	0.21	-0.86	0.20	0.14	-0.01	0.00	0.00
Waste_Dis	0.54	0.21	0.03	-0.24	0.26	0.03	0.16	0.13	0.02	0.19	0.16	0.03
No_Waste_Dis	0.54	0.04	0.12	1.10	0.26	0.12	-0.76	0.13	0.09	-0.87	0.16	0.12
High_Tech	0.62	0.16	0.05	-0.50	0.46	0.09	0.19	0.07	0.02	-0.23	0.09	0.03
Low_Tech	0.62	0.09	0.09	0.92	0.46	0.16	-0.35	0.07	0.04	0.41	0.09	0.06

Note: *Q* = Quality; *m* = mass; *λ* = inertia; *Cd* = Coordinate; *Co* = Correlation; *Ctr* = Contribution.

The MCA biplot (Table 10) suggests two clusters. The blue cluster suggests the association of high levels of digitalization, technology MSR-L4 and MSR-L5 and waste disposal items. Thus, we infer that companies with high levels of digitalisation and technology tend to include more sustainable maintenance performance indicators (SMPIs) in their MDMs. In contrast, companies having lower levels of digitalization and technology do not have capacities to consider many SMPIs but instead focus solely on economic (e.g., downtimes, costs) or environmental (e.g., energy consumption) indicators in their MDM.

In sum, the findings suggest a positive association between digitalization and sustainability aspects within the maintenance function. This suggests that companies with higher technological and digitalization capacities adopt more sustainability performance metrics within MDM. In contrast, companies with lower technological and digitalization capacities do not suggest dependency on sustainability metrics, consequently focusing primarily on specific TBL dimensions (e.g., economic factors—time between failures, time to repair, etc.).

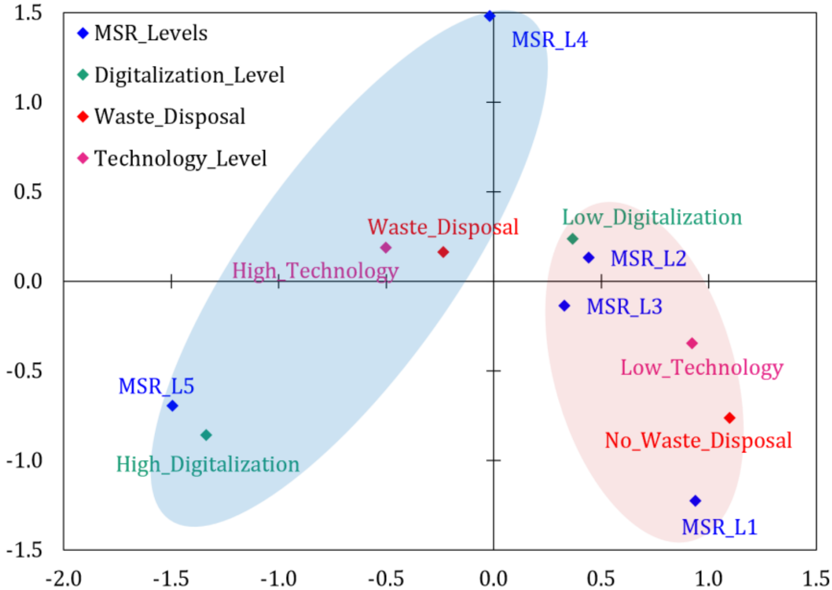

Figure 7: MCA biplot PC1 (x-axis) and PC2 (y-axis). The association of digitalization, waste disposal, technology and MSR levels (blue cluster). The association between lower levels of digitalization, no waste disposal, technology and MSR levels (red cluster).

4. Conclusion

The study performs dual analysis using the Chi-square test of independence and Kendall's Tau test to investigate the relationship between digitalization level and sustainable responsibility factors in decision-making. The findings suggest significant evidence in favour of the relationship between the factors above, suggesting that companies with higher levels of digitalization tend to be more environmentally and socially responsible. Additionally, the MCA analysis suggests that companies with lower levels of digitalization tend to monitor fewer sustainability factors and lack appropriate waste management and recycling practices, presumably due to limited technological capacities.

Several limitations were reported in the study. Namely, the study relies on a preliminary sample of 51 companies, which is still collecting data. Although the sample is not representative, we believe the data will undoubtedly add evidence supporting the hypothesis that digitalization plays a vital role in adopting SM practices. Next, the sample may suffer from the heterogeneity of company size and types of applications in which maintenance practices are performed. This, in turn, may cause bias across findings where micro and small businesses tend to include less digital technologies in their maintenance practices. Lastly, obtained findings regarding the association between different items leveraging MCA, the results are discussed based on the 43% of shared inertia. However, we performed additional analysis using the first four components and found no additional insights about the dependency between items.

The study's implications will undoubtedly play a role for decision- and policy-makers in altering their existing maintenance practices by adopting and increasing their digital capabilities, especially since it becomes easier for engineers and managers to track their performance via sustainability metrics. This offers additional advantages since using energy resources effectively reduces unnecessary waste and improves resource efficiency, ultimately shifting traditional industrial maintenance practices to sustainable maintenance practices.

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