

THESES OF THE DOCTORAL (PhD) DISSERTATION

DAIRY 4.0 MATURITY AND ESG ENABLEMENT IN VISEGRAD GROUP DAIRY PROCESSORS (2019-2024)

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2026

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1. BACKGROUND, OBJECTIVES AND HYPOTHESES OF THE RESEARCH

This thesis presents the main findings of the doctoral dissertation entitled “Dairy 4.0 Maturity and ESG Enablement in Visegrad Group Dairy Processors (2019-2024)”. The dissertation investigates the character and extent of Dairy 4.0 digital maturity among the leading dairy processing companies in the Visegrad Four (Czech Republic, Hungary, Poland, and Slovakia) over the period 2019-2024. The central aim is to characterise what these companies disclose about their digital transformation, to understand the role that ESG-related reporting plays as a primary channel through which that transformation becomes publicly observable, and to examine the temporal dynamics and financial correlates of disclosure-visible Dairy 4.0 adoption.

The digitalisation of agri-food systems has emerged as one of the defining transformations of early 21st-century food production. Across Europe, dairy processing stands at a critical juncture: simultaneously pressed by tightening sustainability regulation, rising consumer expectations for supply chain transparency, and the technological opportunities created by Industry 4.0 (I4.0) digital tools. Blockchain, Artificial Intelligence (AI), the Internet of Things (IoT), Big Data Analytics, 3D Printing, and Robotics – collectively branded as Dairy 4.0 – are increasingly cited as the primary levers through which dairy processors can achieve the twin goals of operational efficiency and ESG (Environmental, Social, and Governance) performance (HASSOUN et al., 2023). Yet despite considerable academic interest in each of these technologies individually, systematic cross-national evidence on how digital maturity manifests in the corporate documentation of dairy processors remains scarce.

This gap is particularly pronounced in the Visegrad Four (V4) region – comprising the Czech Republic, Hungary, Poland, and Slovakia – where EU membership since 2004 has created a shared regulatory and policy framework, while structural differences in market concentration, ownership patterns, and institutional embeddedness have produced meaningfully heterogeneous digital transformation trajectories. The V4 together account for approximately 13–15% of EU total milk production (EUROSTAT, 2025), yet no existing study has constructed a longitudinal, company-level panel of Dairy 4.0 disclosure maturity for this region, nor tested systematically whether and how ESG-related disclosure functions as the primary channel through which digital transformation becomes publicly observable in this sector.

A central motivation for this study is the observation that, in the V4 dairy context, digital transformation is largely invisible through the lens that the existing literature uses – technology

adoption surveys, farm-level trials, and engineering assessments – because most of the relevant evidence is embedded in publicly available corporate and regulatory documents. Statutory annual filings, Integrated Pollution Prevention and Control (IPPC) environmental permits, and sustainability reports collectively constitute a rich and underutilised source of evidence for digital capability assessment at the processing company level. Crucially, the preliminary evidence motivating this study is that ESG-related measurement and reporting infrastructure appears far more prominently in these documents than advanced technology capabilities such as AI or analytics – a pattern that, if confirmed at scale, would represent a new empirical regularity with important implications for policy, measurement, and the academic literature on green–digital transition coupling.

The value of this study resides in providing the first systematic, multi-country, longitudinal assessment of Dairy 4.0 maturity among V4 dairy processors. By developing and applying an original disclosure-based coding instrument – the Dairy 4.0 ESG Indicator Template – the dissertation generates a replicable, traceable company-year panel linking coded digital capability indicators to documentary evidence. This panel serves not only as an empirical contribution in its own right, but also as a proof-of-concept for a broader methodological approach to measuring digital transformation in sectors where internal deployment data is not directly observable by external researchers.

The study is also timely from a policy perspective. The Corporate Sustainability Reporting Directive (CSRD), entering into force progressively from 2025, will substantially expand mandatory structured ESG disclosure obligations to a large fraction of V4 dairy processors. Understanding the current state of digital ESG infrastructure – and the institutional mechanisms driving its adoption – is therefore directly relevant to both regulatory design and industry strategy for the CSRD transition period.

1.1 Research aims

This dissertation investigates the character and extent of Dairy 4.0 digital maturity among the leading dairy processing companies in the Visegrad Four over the period 2019-2024. The central aim is to characterise what these companies disclose about their digital transformation, to understand the role that ESG-related reporting plays as a primary channel through which that transformation becomes publicly observable, and to examine the temporal dynamics and financial correlates of disclosure-visible Dairy 4.0 adoption. Rather than assuming that higher disclosure scores translate directly into superior financial performance, the study treats the disclosure itself – what is reported, through which documents, and in which institutional contexts – as the primary object of empirical inquiry.

1.2 Research objectives

Six objectives organise the empirical work:

1. Map the current state of Dairy 4.0 adoption among leading dairy processors in the V4, using a structured disclosure-based coding instrument applied to publicly available corporate, regulatory, and sustainability documents (2019-2024).
2. Examine cross-national heterogeneity in D4 maturity across the Czech Republic, Hungary, Poland, and Slovakia, identifying differences in the level, composition, and institutional drivers of digital technology disclosure.
3. Analyse the temporal dynamics of D4 disclosure over the 2019-2024 period, testing whether aggregate disclosure intensity increases within firms over time and characterising the drivers of any observed improvement.
4. Investigate the relationship between D4 maturity scores and financial performance indicators (turnover and profit margin) among V4 dairy processors, distinguishing cross-sectional associations from within-firm dynamics using fixed-effects panel models.
5. Examine the ESG-Dairy 4.0 nexus: establish whether ESG Enablement is the dominant D4 sub-dimension, characterise the institutional mechanisms driving that dominance, and explore whether ESG disclosure shows evidence of leading broader technology adoption.
6. Draw out the implications of the empirical findings for how digital transformation should be measured, supported, and governed in the V4 dairy sector and more broadly in Central-Eastern European agri-food industries operating under increasingly demanding EU sustainability reporting obligations.

1.3 Research questions

The overarching research question is: *How extensive is Dairy 4.0 digital maturity among leading dairy processors in the Visegrad Four, and what role does ESG enablement play as the primary channel through which digital transformation is disclosed?* Four sub-questions structure the empirical analysis:

1. What is the current level and composition of Dairy 4.0 adoption among major dairy processors in the Czech Republic, Hungary, Poland, and Slovakia? How does this vary across countries and firm types?

2. Has disclosure-visible Dairy 4.0 maturity increased over the 2019-2024 period? If so, is this increase driven by genuine deepening of digital capability within firms, or by compositional and documentary coverage effects?
3. To what extent does Dairy 4.0 disclosure intensity correlate with financial performance (revenue and profit margin) among V4 dairy processors? Does this association reflect genuine adoption-performance dynamics or firm-size effects?
4. Why does ESG Enablement dominate Dairy 4.0 disclosure in the V4 context? What institutional mechanisms explain its systematic advantage over operational technology dimensions, and is there exploratory evidence that ESG disclosure precedes and is positively associated with subsequent technology disclosure in temporal sequence?

1.4 Research hypotheses

Four hypotheses are tested across four analytical domains: H1 addresses cross-national heterogeneity, H2 temporal dynamics, H3 financial performance, and H4 the ESG-Dairy 4.0 nexus. H4 is addressed through two related propositions: H4a tests the dominance claim confirmatorily; H4b examines temporal disclosure sequencing as an exploratory supplement.

H1 (Cross-national heterogeneity): The distribution of Dairy 4.0 maturity scores differs significantly across the four V4 countries, reflecting structural differences in firm ownership, market concentration, regulatory exposure, and document availability.

H2 (Temporal dynamics): Aggregate Dairy 4.0 disclosure intensity in the V4 increases significantly between 2019 and 2024; however, this increase is driven primarily by growth in document volume and between-firm compositional change rather than by within-firm content deepening.

H3 (Financial performance): The positive cross-sectional association between Dairy 4.0 maturity score and firm revenue is primarily attributable to firm-size heterogeneity rather than to an independent adoption-performance dynamic; within-firm panel models controlling for firm-level fixed effects are hypothesised to show no significant association between D4 disclosure intensity and contemporaneous turnover or profit margin, while the supplementary lagged growth specification is likewise hypothesised to show no significant relationship, across the 2019-2024 panel.

H4a (ESG dominance – confirmatory): The ESG enablement sub-dimension is the highest-scoring and most widely adopted Dairy 4.0 dimension across the full panel, significantly and stochastically dominating all operational technology dimensions in mean score, adoption rate, and verified-evidence achievement rate.

H4b (Disclosure sequencing – exploratory): Lagged ESG disclosure (ESG_{t-1}) is expected to show a positive association with subsequent technology sub-dimension scores (tech_sum_t), a pattern consistent with ESG functioning as a disclosure precursor rather than a lagging consequence of technology adoption.

1.5 Research approach

The study follows a deductive research logic, deriving hypotheses from established theoretical frameworks – institutional isomorphism (DIMAGGIO & POWELL, 1983), global value chain theory (GEREFFI et al., 2005), and the digital maturity literature – before evaluating them against systematically collected empirical evidence. This approach is well established in management and agri-food research and is appropriate for a study whose primary goal is hypothesis testing in a multi-country comparative context (BRYMAN, 2016).

The research strategy is a longitudinal quantitative panel study with a disclosure-based measurement design. Rather than conducting surveys or interviews, the dissertation operationalises digital maturity through publicly available documentary evidence, treating companies' corporate and regulatory documents as the empirical field. This strategy is appropriate given that internal technology deployment data is not accessible to external researchers for the majority of V4 dairy processors, and because disclosure behaviour is itself theoretically important – what firms choose to communicate about their digital activities is as meaningful as what they have deployed, particularly in the context of evolving ESG reporting obligations.

The time horizon is longitudinal: a six-year panel (2019-2024) is used to examine temporal dynamics and to enable the within-firm fixed-effects analysis required by H3. The cross-sectional dimension covers 80 companies across four V4 countries, providing sufficient variation to test H1. The combination of cross-sectional and temporal dimensions places the study in the tradition of panel data research in management (WOOLDRIDGE, 2019).

2. DATABASE AND METHODOLOGY

To make it precise and easy for the reader to understand how this research was carried out in the methodological context, which techniques were used, and what types of data were collected, this chapter sets out the full research design, data collection procedure, measurement instrument, and analytical strategy.

2.1 Research design and philosophy

The research adopts a post-positivist epistemological orientation (POPPER, 1959), which holds that empirical analysis can reveal provisional patterns and associations in social phenomena

rather than verify theoretical claims with certainty. The approach is primarily deductive: four hypotheses are specified in advance on the basis of theoretical priors, then evaluated against systematically coded empirical evidence (BRYMAN, 2016). The coding instrument was designed to capture the dimensions of digital transformation identified in prior research as most relevant to dairy processing contexts, ensuring that the deductive framework is theory-informed throughout.

The research strategy is a quantitative longitudinal panel study. A panel design is appropriate because the research questions require both cross-sectional comparison (H1: cross-national heterogeneity) and temporal analysis (H2: trends over time), and because the causal identification strategy for H3 depends on within-firm variation over multiple years. The disclosure-based measurement approach is chosen because digital transformation is not directly observable for external researchers in this sector – most implementation details are internal, and disclosure incentives vary substantially by firm size, ownership, and institutional context.

2.2 Sample and data collection

The dataset covers 80 dairy processing companies – 20 per Visegrad country – selected to represent the leading tier of the dairy industry in each national context. The selection criterion was company size, measured by estimated dairy revenue or reported milk intake volume, drawing on national company registers, trade statistics, and industry directories. This purposive criterion ensures that the sample captures firms with the scale and institutional embeddedness likely to generate sufficient documentary evidence for coding, while remaining representative of the leading processing tier rather than the full population of dairy firms.

A total of 1,148 documents were collected and coded across the 80 companies and the 2019-2024 reporting period, yielding 471 company-year panel observations. Documents were drawn from five source categories: (1) statutory filings in national company registers (annual financial statements, management reports); (2) IPPC environmental permits and monitoring records from national environmental authorities; (3) sustainability and ESG reports at company or group level; (4) certification records and audit statements; and (5) corporate website disclosures and trade publications. Each document was assigned to a company-year cell, classified by document type and source institution, and entered into the coding database before scoring.

The panel is unbalanced: 74 of 80 companies are observed in all six years; the remaining six have gaps due to incomplete public disclosure in one or more years. Mean documents per company-year is 2.44, ranging from a minimum of 1 to a maximum of 12. Document volume increases substantially over the study period, rising from 141 documents in 2019 to 270 in 2024, reflecting the growing availability of sustainability and ESG disclosures and expanding IPPC

permit coverage across the region. Slovakia accounts for the highest document count (405), though this is primarily driven by regulatory permit documents, whereas Poland and Czech Republic show higher proportions of annual and sustainability reports.

Table 1. Panel composition by country

Country	Companies	Total documents	Panel observations
Czech Republic	20	233	119
Hungary	20	220	119
Poland	20	290	115
Slovakia	20	405	118
V4 total	80	1,148	471

Source: Constructed by author (2025)

2.3 Measurement instrument

The primary measurement instrument is the Dairy 4.0 ESG Indicator Template, an original structured coding template constructed by the author. The template was developed through a three-stage process: (1) a systematic review of the Dairy 4.0 and Industry 4.0 maturity assessment literature to identify the core technology and governance dimensions that constitute Dairy 4.0 capability; (2) a pilot coding exercise on a sub-sample of 20 company-years to test the operationalisation and refine ambiguous scoring criteria; and (3) a final revision that added the evidence-source tracking and quality classification features required for the institutional analysis in H4.

The template covers eight Dairy 4.0 adoption sub-dimensions, each scored on a 0–2 ordinal scale: 0 = no codable evidence; 1 = mentioned or basic reference; 2 = explicit, substantiated evidence with specific details. The eight sub-dimensions are: (1) Strategy and Governance; (2) IoT and Sensing; (3) Automation and Robotics; (4) MES/SCADA and ERP; (5) Quality and Traceability; (6) Analytics and AI; (7) Digital Supply-Chain Integration; and (8) ESG Measurement Enablement. Coding was restricted to explicitly stated evidence; ambiguous or purely promotional language was scored conservatively at 0 or 1. Each coded record was linked to its source document, document type, and an evidence quality classification (qualitative vs. numerical).

The D4 Total score is the sum of all eight sub-dimension scores, with a maximum of 16. The instrument's validity is supported on three dimensions: discriminant validity (markedly different score distributions across sub-dimensions, consistent with theoretical priors); construct validity (a coherent ESG-centred correlation structure across sub-dimensions); and

partial predictive validity (a significant cross-sectional revenue correlation consistent with the adoption-performance literature).

2.4 Analytical methods

H1 (cross-national heterogeneity) is tested using the Kruskal-Wallis H test, a non-parametric one-way analysis of variance appropriate for ordinal-scaled, non-normally distributed D4 scores across four country groups. Statistically significant results are followed by Dunn post-hoc pairwise comparisons with Bonferroni correction to identify which country pairs differ significantly.

H2 (temporal dynamics) is tested in two stages. The aggregate trend across the six-year panel is evaluated using a Kruskal-Wallis test across year groups and a Mann-Whitney comparison of the 2024 and 2019 distributions. The within-firm content-deepening component – the second part of H2 – is tested using a two-way fixed-effects (FE) panel regression with firm and year dummy variables as the primary specification, complemented by a content intensity analysis using D4 score per document as the outcome variable. The FE design absorbs all time-invariant firm heterogeneity, isolating purely within-firm variation in disclosure intensity over time.

H3 (financial performance) uses a three-layer analytical strategy. Cross-sectional Spearman rank correlations between D4 Total score and $\log(\text{Turnover_EUR})$, and between D4 Total and Profit Margin, establish the baseline associations. Two-way FE regressions with firm-clustered standard errors (sandwich estimator, small-sample corrected) then test whether these associations reflect genuine within-firm adoption-performance dynamics or firm-size confounds. A one-year lagged specification ($D4_{i,t-1} \rightarrow \Delta \ln(\text{Turnover}_t)$) provides a forward-looking robustness check.

H4 (ESG dominance and disclosure sequencing) uses sub-dimension mean comparison across all eight dimensions, Mann-Whitney stochastic dominance tests of ESG Enablement against each of the seven technology sub-dimensions (one-tailed, significance threshold $\alpha = 0.05$), and a Spearman lagged correlation ($\text{ESG}_t \rightarrow \text{tech_sum}_t$) across 390 company-year transitions. The partial correlation between ESG Enablement and D4 Total, controlling for Automation & Robotics, is computed to confirm the independent ESG contribution.

3. MAIN FINDINGS OF THE DISSERTATION

This chapter presents the results of the four analytical components of the dissertation, organised around the four research hypotheses. All findings are based on 471 company-year observations from 80 V4 dairy processors across 2019-2024.

3.1 Descriptive profile of the V4 panel

Across the full panel of 471 company-year observations, the mean D4 Total score is 2.51 (SD = 2.38; median = 2.0; range 0–16). Nearly three in ten company-years (28.5%) show no codable evidence of digital transformation in any of the eight sub-dimensions. This high zero rate reflects a structural feature of the V4 dairy sector: a substantial share of even relatively large processors do not communicate digital capability through publicly available documents, either because they have not invested in digital systems, or because they lack the reporting infrastructure to document activities that may already be deployed.

Among the eight sub-dimensions, ESG Measurement Enablement is the highest-scoring dimension by a wide margin, with a mean score of 0.822 and an adoption rate of 53.1%. Automation and Robotics is the second-ranking technology dimension (mean 0.529, adoption 41.0%), followed by MES/SCADA & ERP (mean 0.382, adoption 34.0%). Analytics and AI is the lowest-scoring dimension (mean 0.130, adoption 11.0%), confirming that advanced data-driven capabilities remain nascent in the V4 dairy processing sector during the observation period. The ESG-to-technology gap is consistent across all four countries and all six years of the panel.

Table 2. Dairy 4.0 sub-dimension scores across the full V4 panel

Sub-dimension	Mean score	Adoption rate (%)	Score = 2 rate (%)
ESG Measurement Enablement	0.822	53.1%	29.1%
Automation & Robotics	0.529	41.0%	11.9%
MES/SCADA & ERP	0.382	34.0%	4.2%
Quality & Traceability	0.340	28.9%	5.1%
Strategy & Governance	0.321	27.8%	4.2%
IoT & Sensing	0.285	24.6%	3.8%
Digital Supply-Chain Integration	0.163	13.8%	2.5%
Analytics & AI	0.130	11.0%	1.5%

Source: Constructed by author (2026)

3.2 H1 – Cross-national heterogeneity (Supported)

The Kruskal-Wallis test confirms significant cross-national heterogeneity in D4 Total scores across the four V4 countries ($H = 14.28$, $df = 3$, $p = 0.003$). Dunn post-hoc tests with Bonferroni correction identify Slovakia as the significantly lower-scoring country relative to both Czech Republic ($z = 3.26$, $p = 0.007$) and Hungary ($z = 3.28$, $p = 0.006$). The remaining pairwise

comparisons (Czech Republic–Hungary, Czech Republic–Poland, Hungary–Poland, Poland–Slovakia) are non-significant after correction.

Table 3. D4 maturity scores by Visegrad country (2019–2024)

Indicator	Czech Republic	Hungary	Poland	Slovakia
Mean D4 score	2.61	2.84	2.70	1.88
Median	3.0	3.0	2.0	2.0
Zero rate (%)	15%	23%	36%	41%
Max score observed	11	14	16	7

Source: Constructed by author (2026)

Czech Republic shows the narrowest distribution with the lowest zero rate (15%) and a median of 3.0, consistent with broad but not extreme D4 documentation driven by a relatively compact group of consistently disclosing firms. Hungary's above-average mean (2.84) is driven by a combination of high-scoring multinational subsidiaries – FrieslandCampina, Danone Hungary Kft (mean = 5.67), and Savencia Fromage & Dairy Hungary – and the domestic cooperative Sole-Mizo Zrt (mean = 6.17 across the panel), which is the highest-scoring Hungarian firm. Hungary's median of 3.0 and zero rate of 23% reflect these multinationals lifting the country mean above all other V4 countries except when compared directly with the Czech Republic's more evenly distributed scores.

Poland presents the most bimodal profile: the highest maximum in the panel (16, achieved by Zott Polska in 2022), a zero rate of 36%, and the largest within-country variation. This pattern reflects the structural duality of Polish dairy processing – a small number of large cooperative processors (SM Mlekpól, Grupa Mlekovita, Grupa Polmlek) disclosing at very high levels alongside a large number of domestic firms that produce minimal documentary evidence. Slovakia shows the flattest profile: a median of 2.0 and a 41% zero rate, consistent with the country's fragmented ownership structure, limited multinational presence, and the predominance of IPPC permit documents (which contribute to ESG evidence but not to technology dimensions) in the Slovak sub-sample. H1 is supported.

3.3 H2 – Temporal dynamics (Supported, both parts)

The aggregate D4 Total score rises from a mean of 1.87 in 2019 to 3.52 in 2024, an 88% increase over six years. The zero rate declines from 39.5% in 2019 to 12.7% in 2024, indicating that a large number of previously non-disclosing firms entered the non-zero disclosure space over the period. Both the Kruskal-Wallis test across all six years ($H = 20.90$, $p < 0.001$) and the

Mann-Whitney comparison of 2024 versus 2019 distributions ($U = 4,106$, $p < 0.001$) confirm the improvement is statistically significant. Mean documents per company-year rose from 1.86 in 2019 to 3.42 in 2024, an 84% increase in document volume over the panel period.

Table 4. Temporal evolution of D4 disclosure intensity across the V4 panel (2019-2024)

Indicator	2019	2020	2021	2022	2023	2024
Mean D4 Total	1.87	2.04	2.22	2.71	2.68	3.52
Zero rate (%)	39.5%	32.9%	30.8%	29.1%	26.2%	12.7%
ESG Enablement mean	0.697	0.772	0.821	0.873	0.825	0.937

Source: Constructed by author (2026)

The within-firm component, however, is non-significant. The two-way fixed-effects regression (firm + year effects) yields $\beta = 0.296$ ($SE = 0.444$, $p = 0.505$). A parallel analysis using content intensity – D4 score per document – as the outcome confirms this null result: $\beta = 0.031$ ($p = 0.894$). The modal year-to-year transition in D4 scores is stasis: 52.9% of transitions show $\Delta D4 = 0$, meaning the majority of firms maintain the same disclosure profile from one year to the next. When scores do change, movements are discrete integer-valued jumps rather than the continuous linear improvement assumed by the FE specification, consistent with the lumpy nature of new document-type adoption.

The aggregate improvement is geographically concentrated: Poland alone drives the V4 trend (Spearman $\rho = 0.434$, $p < 0.001$ for the Poland time trend), with its mean score rising from 0.83 in 2019 to 4.75 in 2024. Hungary and Slovakia show no statistically significant temporal trend. The Polish trajectory reflects the entry of large cooperative processors (SM Mlekpól, Grupa Mlekovita, Grupa Polmlek) into the high-disclosure space from 2021 onward, consistent with the compositional-change explanation rather than within-firm content deepening. Both parts of H2 are supported.

3.4 H3 – Financial performance (Supported)

The cross-sectional Spearman correlation between D4 Total score and $\log(\text{Turnover_EUR})$ is positive and significant ($\rho = 0.285$, 95% CI [0.181, 0.383], $p < 0.001$), consistent with the first part of H3: larger firms score higher on D4 disclosure. This association holds within all four V4 countries (Spearman ρ ranging from 0.273 in Czech Republic to 0.757 in Slovakia, though the Slovak coefficient reflects a small sub-sample). At the sub-dimension level, IoT & Sensing ($\rho = 0.349$) and ESG Enablement ($\rho = 0.319$) show the strongest positive correlations with revenue.

However, the two-way FE regression with $\log(\text{Turnover_EUR})$ as outcome yields $\beta = 0.666$ ($\text{SE} = 0.763$, $p = 0.383$, firm-clustered SEs), and with Profit Margin as outcome $\beta = -1.624$ ($\text{SE} = 2.778$, $p = 0.559$) – both entirely non-significant. The Spearman correlation between D4 Total and Profit Margin is $\rho = -0.094$ ($p = 0.098$, non-significant). The one-year lagged specification produces no forward-looking signal ($\rho = 0.016$, $p = 0.798$). The null FE results confirm that the cross-sectional correlation is a firm-size artefact: larger firms both score higher on D4 and generate higher revenues, but within-firm disclosure variation does not predict financial performance. H3 is supported.

Three sensitivity checks were performed: (1) restricting to the 74 firms observed in all six years (balanced panel) does not alter the null conclusion; (2) using the sum of sub-dimension maxima rather than the max-of-document-totals composite yields an identical null; (3) the cross-sectional $\rho = 0.285$ holds within each V4 country individually, ruling out any single-country driver.

3.5 H4 – ESG dominance and disclosure sequencing (Supported, all parts)

ESG Enablement is the structurally dominant D4 sub-dimension across every metric in the scoring framework. Its mean score of 0.822 is 2.68 times the average of the remaining seven technology sub-dimensions (mean 0.307). Its adoption rate of 53.1% is 1.3 times higher than the next most-adopted dimension (Automation & Robotics, 41.0%) and almost five times higher than Analytics & AI (11.0%). Its verified-evidence (score = 2) rate of 29.1% is 2.4 times higher than Automation (11.9%) and 19 times higher than Analytics & AI (1.5%). Mann-Whitney U tests confirm stochastic dominance of ESG Enablement over all seven technology comparators at $p < 0.001$ (one-tailed). ESG Enablement was already the highest-scoring dimension in 2019 (mean 0.697), when Analytics & AI scored a mean of just 0.026 – a ratio of more than 26:1 that has not narrowed over the observation window. H4a is supported.

The sub-dimension correlation structure confirms ESG as the integrating dimension: Spearman correlations between ESG Enablement and each technology sub-dimension range from $\rho = 0.246$ (Analytics & AI) to $\rho = 0.402$ (IoT & Sensing), all significant at $p < 0.001$. The partial correlation between ESG and D4 Total, controlling for Automation & Robotics, is $\rho = 0.620$ ($p < 0.001$), confirming that ESG explains substantial D4 variance in its own right, independently of the strongest technology co-predictor.

Evidence source analysis reveals that IPPC environmental permits account for 27.3% of non-zero ESG Enablement evidence records while contributing zero records to any operational technology dimension. This confirms that EU environmental permitting mandates generate measurable digital monitoring infrastructure as a by-product of regulatory compliance,

independently of firms' voluntary digital adoption strategies. Annual and Management Reports are the largest single source of ESG evidence (52.3%), followed by IPPC permits (27.3%) and dedicated Sustainability/ESG reports (13.6%).

The exploratory lagged analysis across 390 company-year transitions finds that ESG disclosure at year $t-1$ is positively and significantly associated with technology disclosure at year t (Spearman $\rho = 0.438$, 95% CI [0.354, 0.515], $p < 0.001$). This temporal precedence is consistent with ESG functioning as a disclosure gateway – firms that first document environmental monitoring and sustainability governance capabilities subsequently disclose operational technology across multiple D4 dimensions. The contemporaneous ESG-tech correlation ($\rho = 0.567$) is stronger than the lagged association, confirming that the relationship is not purely anticipatory, but the directional pattern supports the gateway mechanism at the margin. H4b is supported.

3.6 Hypothesis test results summary

Table 5. Hypothesis test results summary

Hyp.	Domain	Hypothesis (abbreviated)	Key evidence	Verdict
H1	Cross-national heterogeneity	D4 maturity scores differ significantly across the four V4 countries, reflecting structural differences in ownership, market concentration, regulatory exposure, and document availability.	Kruskal-Wallis $H = 14.28$, $p = 0.003$; Dunn post-hoc: Slovakia significantly lower than Czech Republic ($p = 0.007$) and Hungary ($p = 0.006$).	SUPPORTED
H2	Temporal dynamics	Aggregate D4 disclosure increases significantly 2019-2024, but is driven by document volume and between-firm compositional change rather than within-firm content deepening.	Aggregate: KW $H = 20.90$, $p < 0.001$; Mann-Whitney 2024 vs. 2019, $U = 4,106$, $p < 0.001$. Within-firm FE: $\beta = 0.294$, $p = 0.552$ (non-significant). Content intensity FE: $\beta = 0.031$, $p = 0.894$.	SUPPORTED (both parts)
H3	Financial performance	The cross-sectional D4-revenue correlation reflects a firm-size effect; within-firm FE models yield no significant positive association between D4 score and contemporaneous turnover level or profit margin; the lagged growth specification ($D4_{i,t-1} \rightarrow \Delta \ln(\text{Turnover}_t)$) is likewise null.	Cross-sectional $\rho = 0.285$, $p < 0.001$. FE Turnover: $\beta = 0.666$, $SE = 0.763$, $p = 0.383$, $n = 320$ (firm-clustered SEs). FE Profit Margin: $\beta = -1.624$, $SE = 2.778$, $p = 0.559$, $n = 308$. Doc_count control $\beta \approx 0.63$, $p < 0.001$. Lagged $\rho = 0.016$, $p = 0.798$.	SUPPORTED

H4	ESG dominance	ESG Enablement is the highest-scoring and most widely adopted D4 dimension, stochastically dominating all operational technology dimensions in mean score, adoption rate, and verified-evidence rate. Lagged ESG positively associated with subsequent technology disclosure ($\rho = 0.438$, $p < 0.001$, $n = 390$).	ESG mean 0.822 vs. next-highest Automation 0.529; adoption rate 53.1% vs. 41.0%; score=2 rate 29.1% vs. 11.9%. Mann-Whitney dominance over all tech comparators $p < 0.001$. Lagged: ρ (ESG _{t-1} , tech _t) = 0.438, $p < 0.001$, $n = 390$.	SUPPORTED (all parts)
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Note. FE = two-way fixed-effects regression (firm and year effects); H3 FE standard errors are firm-clustered (sandwich estimator, small-sample corrected). H1/H2/H3 non-parametric tests are two-tailed; H4a Mann-Whitney tests are one-tailed (alternative: ESG > tech dimension). Significance threshold $\alpha = 0.05$. Verdicts based on the full panel of $N = 471$ company-year observations from 80 V4 dairy processors, 2019-2024.

Source: Constructed by author (2026)

4. CONCLUSIONS

This dissertation set out to characterise the Dairy 4.0 digital maturity landscape across the Visegrad Four dairy processing sector, to analyse its temporal dynamics and financial correlates, and to examine the institutional role of ESG disclosure as the primary channel through which digital transformation is communicated in the industry. The evidence assembled across 471 company-year observations and 1,148 documents yields four interconnected conclusions.

The first and most fundamental conclusion is that ESG Measurement Enablement is not merely a component of Dairy 4.0 maturity in the V4 context – it is the structurally dominant dimension, achieving a mean score 2.68 times the average of the seven technology sub-dimensions and stochastically dominating each comparator at conventional significance levels. This dominance is explained by three complementary institutional mechanisms. First, IPPC environmental permitting mandates require large dairy installations to install digital monitoring infrastructure and generate environmental documentation as a condition of operating compliance, creating a mandatory floor of ESG-codable evidence with no equivalent for any technology dimension. Second, a substantial share of V4 dairy processing capacity is embedded in Western European multinational value chains (FrieslandCampina, Danone, Lactalis, Savencia, Zott), whose group-level sustainability reporting frameworks generate ESG Enablement evidence through parent-company infrastructure rather than local investment decisions. Third, ESG-related language – energy monitoring, waste reduction, environmental compliance – is more accessible to narrative reporting than the substantiated operational evidence required to score IoT, Automation, or Analytics at level 2.

The second conclusion is that aggregate D4 disclosure has improved substantially over the six-year window – rising 88% in mean score and reducing the zero rate from 39.5% to 12.7% – but this improvement is almost entirely attributable to document volume growth and between-firm compositional change, not to within-firm content deepening. The fixed-effects analysis, which strips out all time-invariant firm heterogeneity and common year shocks, finds no significant linear trend in D4 disclosure intensity within firms ($\beta = 0.296$, $p = 0.505$). The majority of firms maintain the same disclosure profile year on year, and the aggregate improvement is driven primarily by Poland – specifically by a small cohort of large cooperative processors (SM Mlekpól, Grupa Mlekovita, Grupa Polmlek) entering the high-disclosure space after 2021. This finding implies that policy assessments of the sector's digital progress based on aggregate statistics will significantly overstate actual within-firm capability improvement.

The third conclusion is that the D4-revenue correlation, while significant in cross-section ($\rho = 0.285$), is a firm-size artefact. Within-firm fixed-effects models yield null results for both turnover ($\beta = 0.666$, $p = 0.383$) and profit margin ($\beta = -1.624$, $p = 0.559$), confirming that disclosure variation does not predict financial performance in the six-year window available. This finding is consistent with theoretical predictions for capital-intensive technology investments over short horizons, but it also points to a deeper limitation: the D4 score captures reporting sophistication and institutional embeddedness as much as genuine technology deployment, making it an insufficient proxy for adoption-performance inference.

The fourth conclusion concerns the temporal structure of the ESG-technology relationship. The lagged analysis shows that ESG disclosure at year $t-1$ predicts technology disclosure at year t ($\rho = 0.438$, $p < 0.001$), consistent with the gateway hypothesis: environmental monitoring capability investment precedes and enables broader digital disclosure maturity. For Central-Eastern European food processors, the pathway to multi-dimensional digital disclosure appears to run through environmental compliance rather than through the IoT-automation-analytics progression assumed by most Industry 4.0 readiness frameworks. This finding should reshape how digital transformation is assessed, supported, and governed in the region, and suggests that the green and digital transitions are institutionally coupled rather than parallel policy streams.

5. NEW AND NOVEL RESULTS OF THE DISSERTATION

The dissertation presents five original contributions to knowledge that are, to the best of the author's knowledge, new to the Dairy 4.0 literature and to the broader literature on digital transformation measurement in food processing.

5.1 The ESG-D4 Nexus as a new empirical regularity

I have demonstrated for the first time that ESG Enablement is the dominant sub-dimension in a systematic, cross-national, multi-year Dairy 4.0 maturity assessment – with a mean score 2.68 times the average of the seven technology sub-dimensions, an adoption rate 1.3 times higher than the strongest technology comparator (Automation & Robotics, 41.0%), and a verified-evidence rate 2.4 times higher than Automation (29.1% vs. 11.9%). The existing Dairy 4.0 literature characterises the sector's digitalisation trajectory through technology-centric lenses – IoT, robotics, data analytics – without identifying the institutional channels through which digital capability becomes visible in public documents. The ESG-dominant pattern documented here constitutes a new empirical regularity that is likely to be replicated in other food sectors with similar regulatory exposure and in other Central-Eastern European manufacturing contexts with similar GVC integration patterns.

5.2 The IPPC Permit as an unintended driver of digital environmental disclosure

I have established that IPPC environmental permits account for 27.3% of all non-zero ESG Enablement evidence records in the V4 dairy panel while contributing zero records to any operational technology dimension – identifying, for the first time, the EU's environmental permitting regime as a digital capability diffusion mechanism in the food processing sector. This finding extends coercive isomorphism theory (DIMAGGIO & POWELL, 1983) from organisational practice adoption to digital capability acquisition, demonstrating that regulatory environmental compliance mandates generate measurable digital monitoring infrastructure as a by-product. Environmental regulation is performing implicit digital policy work that has not been credited in Industry 4.0 strategy assessments, and the forthcoming tightening of reporting requirements under CSRD and ESRS can be expected to accelerate this mechanism further.

5.3 The disclosure archetype taxonomy

I have identified and characterised four institutionally distinct firm-level disclosure archetypes in the V4 dairy processing sector – Both (42%), Neither (36%), ESG-only (11%), and Tech-only (11%) – that map the structural segmentation of the sector in ways not previously documented in the Dairy 4.0 literature. The ESG-only archetype captures firms driven by GVC integration without local technology evidence, while the Tech-only archetype reflects technology investment without ESG reporting infrastructure – two firm types with meaningfully different expected responses to forthcoming CSRD reporting requirements. The Neither archetype, at 36% of observations, is particularly significant: these firms are invisible to documentary evidence-based measurement not because they are non-digital, but because they lack the reporting infrastructure to document their activities.

5.4 ESG disclosure sequencing: exploratory temporal association with technology disclosure

I have provided the first longitudinal test of temporal sequencing between ESG and operational technology disclosure in any industrial sector, finding that lagged ESG disclosure (ESG_{t-1}) is positively and significantly associated with subsequent technology disclosure (tech_sum_t, $\rho = 0.438$, $p < 0.001$) across 390 company-year transitions. This finding supports the gateway hypothesis – that environmental monitoring capability investment precedes and is associated with broader digital disclosure maturity – and suggests that for Central-Eastern European food processors, the pathway to multi-dimensional digital disclosure runs through environmental compliance rather than through the IoT-automation-analytics progression assumed by most Industry 4.0 readiness frameworks.

5.5 The D4 measurement framework as a validated assessment instrument

I have developed and validated an original Dairy 4.0 scoring framework – eight sub-dimensions coded on a 0-2 ordinal scale from publicly accessible documents, with evidence-source tracking and quality classification – that constitutes the first replicable, disclosure-based D4 maturity instrument applied at scale in any food processing sector. The framework's validity is confirmed on three dimensions: discriminant validity through markedly different score distributions across sub-dimensions consistent with theoretical priors; construct validity through a coherent correlation structure with ESG as the integrating dimension; and predictive validity partially supported by the cross-sectional revenue correlation and the temporal lagged ESG-technology association. The framework is directly transferable to other food processing sectors and European regions, and all coding decisions are documented with evidence references and excerpts to ensure full reproducibility.

6. PRACTICAL APPLICABILITY OF THE RESULTS

6.1 Recommendations for policymakers

The central policy implication of this dissertation is that the digital and green transitions in the V4 dairy sector are institutionally coupled rather than parallel, and should be designed accordingly. The IPPC environmental permitting regime is already the most effective near-term D4 diffusion instrument in operation – more so than any technology-specific subsidy programme – because it legally requires digital monitoring infrastructure from large processors as a condition of compliance. The forthcoming CSRD expansion will extend this effect to a larger share of the sector. Policymakers should explicitly recognise this co-benefit in CSRD implementation guidance and should resist the temptation to design digital and sustainability policy as separate workstreams.

SME digitalisation support programmes deserve particular attention: the Neither archetype (36% of observations) is invisible to documentary evidence-based measurement not because these firms are non-digital, but because they lack the reporting infrastructure to document their activities. Adoption-support instruments should build disclosure capacity alongside technology capability. Specifically, policymakers should consider: aligning digital transformation subsidies with ESG reporting infrastructure investments; using IPPC permit renewals as catalysts for digital capability assessment and upgrading; and creating V4-level knowledge-sharing platforms that allow smaller processors to share disclosure best practices and reduce the fixed costs of establishing reporting infrastructure.

6.2 Recommendations for dairy industry

Firms in the ESG-only archetype – subsidiaries that have inherited sustainability reporting frameworks from multinational parents – are in a structurally advantageous position for the CSRD period. Their existing environmental monitoring infrastructure is the foundation from which broader technology disclosure can be sequenced: the lagged analysis confirms that ESG documentation at year $t-1$ systematically predicts technology adoption at year t . These firms should treat ESG compliance not as a reporting silo but as a gateway capability, and should deliberately document existing operational technology – automation, MES systems, quality sensing – that is likely already deployed but undisclosed.

Firms in the Neither archetype face a competitive disadvantage as supply chain due diligence requirements tighten; even basic documentation of existing digital activities would improve their positioning for supplier qualification and public funding access. Firms in the Both archetype – those achieving substantiated evidence across multiple D4 dimensions – represent the sector's disclosure frontier. Their challenge is to move from narrative quality to numerical specificity, producing the quantified sustainability performance data that CSRD compliance will require from 2026 onward. Tech-only firms face the most acute mismatch: technology investment without ESG reporting infrastructure will be increasingly penalised in supplier qualification processes, investor ESG screening, and regulatory compliance assessments.

6.3 Limitations

Seven limitations bound the conclusions of this dissertation. Most fundamentally, the D4 score measures what firms communicate about their digital activities, not what they have deployed. All findings should be interpreted as findings about disclosure behaviour rather than operational technology adoption. Second, the sample of 80 companies represents the leading processing tier in each V4 country rather than the full population of dairy enterprises; the findings should not be extrapolated to smaller, family-owned, or minimally-reporting operations that fall

outside this leading tier. Third, and compounding the previous point, is documentary coverage asymmetry: IPPC permits and detailed annual reports are disproportionately available for larger, more institutionally embedded firms, meaning the Neither archetype is likely undercounted and smaller processors are systematically under-represented in the panel. Fourth, all coding was performed by a single coder without a formal inter-coder reliability test; the pilot calibration, evidence traceability, conservative scoring scale, and sensitivity checks described in Section 2.3 compensate for but do not substitute for an independently verified reliability statistic.

Fifth, the six-year observation window, which spans both COVID-19 disruption and the 2022–2023 energy price shock, is too short to detect performance returns from capital-intensive technology investments, and the null financial results should not be read as evidence that dairy digitalisation generates no returns. Sixth, financial cross-country comparisons carry an additional caveat: market-rate currency conversion does not adjust for purchasing power parity, and the HUF's depreciation over the panel period may understate Hungarian revenues in the middle years. Finally, the causal direction of the ESG-technology relationship cannot be resolved from panel data alone – the gateway, reverse, and shared-firm-capability interpretations are all consistent with the observed lagged correlation. Causal identification would require either a quasi-experimental design exploiting regulatory threshold variation or primary investment sequencing data from internal company records.

6.4 Recommendations for researchers

First, a validation study combining documentary D4 scores with primary survey data on actual technology deployment for a sub-sample of the 80 companies would quantify the disclosure-adoption gap and identify which firm types and sub-dimensions are most subject to disclosure bias. Such a validation would substantially strengthen the evidentiary basis for the D4 framework as a measurement instrument.

Second, extending the panel to cover the 2025-2030 CSRD reporting cycle would enable meaningful adoption-performance analysis with verified numerical data and a longer horizon sufficient to detect capital-intensive technology investment returns. The availability of structured, auditable sustainability data under CSRD will fundamentally improve the quality of documentary evidence available for D4 scoring.

Third, a comparative study extending the D4 framework to Western European dairy sectors (Germany, France, Netherlands, Ireland) would test whether ESG dominance is a transitional-economy phenomenon or a general feature of European dairy digitalisation. The hypothesis

would be that Western European firms show higher tech-dimension scores and a smaller ESG advantage, reflecting their earlier position on the S-curve trajectory.

Fourth, a comparative case study of ESG-only firms – focusing on multinational subsidiaries such as FrieslandCampina Hungária and Savencia Slovakia – would provide the micro-level process evidence that panel data cannot supply: the internal governance mechanisms by which parent-company ESG frameworks translate into local digital monitoring capability and the timeline from reporting requirement to technology installation.

Fifth, a regression discontinuity study exploiting variation in IPPC permit thresholds – firms just above versus just below the relevant processing capacity threshold – would provide causal identification of the regulatory pathway's contribution to ESG Enablement adoption, with direct implications for environmental regulation design in the food processing sector.

LIST OF PUBLICATIONS RELATED TO THE DISSERTATION

1. Kovács, K., Juračak, J., Očić, V., Burdiuzha, A., Szűcs, I.: Evaluation of technical efficiency of Hungarian and Croatian livestock sectors using DEA on FADN data. *Journal of Central European Agriculture (Q4)*. 23(4), 909-920, 2022. ISSN: 1332-9049. DOI: <http://dx.doi.org/10.5513/JCEA01/23.4.3513>
2. Burdiuzha, A.: Innovative Development of the Agricultural Sector in the Visegrad Group Countries. *Economic and Regional Studies = Studia Ekonomiczne i Regionalne (Q4)*. 14(1), 1-13, 2021. ISSN: 2083-3725. DOI: <http://dx.doi.org/10.2478/ers-2021-0001>
3. Burdiuzha, A.: Qualitative assessment of precision dairy farming impact on farm sustainability in Ukraine: the farmers' perspective. *SEA - Practical Application of Science*. 9 (27), 163-173, 2021. EISSN: 2360-2554.
4. Burdiuzha, A., Gorokhova, T., Mamatova, L.: Responsible environmental management as a tool for achieving the sustainable development of European countries. *Intellectual Economics (Q1)*. 14(1), 161-183, 2020. ISSN: 1822-8011. DOI: <http://dx.doi.org/10.13165/IE-20-14-1-10>

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Registry number: DEENK/473/2026.PL
Subject: PhD Publication List

Candidate: Anastasiia Burdiuzha
Doctoral School: Doctoral School of Management and Business
MTMT ID: 10073790

List of publications related to the dissertation

Articles, studies (4)

1. Kovács, K., Juračák, J., Očić, V., **Burdiuzha, A.**, Szűcs, I.: Evaluation of technical efficiency of Hungarian and Croatian livestock sectors using DEA on FADN data.
Journal of Central European Agriculture. 23 (4), 909-920, 2022. ISSN: 1332-9049.
DOI: <http://dx.doi.org/10.5513/JCEA01/23.4.3513>
IF: 0.7
2. **Burdiuzha, A.**: Innovative Development of the Agricultural Sector in the Visegrad Group Countries.
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DOI: <http://dx.doi.org/10.13165/IE-20-14-1-10>

Total IF of journals (all publications): 0,7

Total IF of journals (publications related to the dissertation): 0,7

The Candidate's publication data submitted to the Tudóstér have been validated by DEENK on the basis of the Journal Citation Report (Impact Factor) database.



03 July, 2026