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Article

Institutional-Pressure Context and Structural Attenuation in the Twin Transition: Evidence from an Export-Oriented SME Ecosystem in Türkiye

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***Abstract**: This article examines green-transition maturity, digital-transformation capacity, and their organizational articulation within export-oriented SMEs, using institutional pressure as an interpretative context rather than as a directly measured causal variable. Drawing on survey data from 73 manufacturing firms in an export-oriented ecosystem in Türkiye, the study treats the case as a bounded yet analytically revealing setting rather than as a statistical proxy for the country. Item-level maturity scores, normalized indices, dispersion measures, low-maturity concentration ratios, and attenuation metrics are used to assess awareness-, implementation-, and integration-intensive indicator classes. The findings show uneven progress across the green and digital domains, with the single-item integration signal descriptively lower than the two multi-item domain scores. Carbon accounting awareness, CBAM knowledge, digital strategy, and cybersecurity perform relatively better, whereas life-cycle analysis, green finance utilization, Digital Product Passport readiness, and digital investment return measurement remain fragile. The study interprets the observed cross-sectional maturity gradient as structural attenuation in an institutional-pressure context and argues that the central challenge lies in SMEs' limited ability to convert compliance pressure into integrated organizational transformation.*

***Keywords**: twin transition; SMEs; institutional pressure; green transition; digital transformation*

1. Introduction

Over the past decade, firms have faced two increasingly interdependent pressures: the green transition and digital transformation. The former calls for lower carbon intensity, greater resource efficiency, and more systematic environmental governance; the latter requires data-driven routines, digital infrastructure, and performance monitoring embedded in day-to-day management. Agendas once treated separately are now experienced by many firms as a single strategic challenge.

This convergence has been accelerated by the European Green Deal and related regulatory developments. Instruments such as the Carbon Border Adjustment Mechanism (CBAM; Regulation (EU) 2023/956), the Corporate Sustainability Reporting Directive (CSRD; Directive (EU) 2022/2464), and the emerging Digital Product Passport (DPP) framework under the Ecodesign for Sustainable Products Regulation have made sustainability a more measurable, auditable, and data-intensive governance requirement (European Commission, 2019; European Commission, 2020; European Union, 2022, 2023, 2024). For firms integrated into European value chains, environmental performance is therefore becoming a condition of market access, buyer confidence, and competitive positioning.

Research on the green transition shows that regulation does not operate only as a cost burden. Porter and van der Linde (1995) argue that well-designed regulation may stimulate innovation, while Hart (1995) links environmental capability to strategic advantage.

Yet these two literatures have often evolved in parallel. Policy discourse increasingly presents them as a twin transition because digital tools are expected to support traceability, optimization, and system integration, but firm-level evidence on actual organizational coupling remains limited (Bocken & Geradts, 2020; George et al., 2021; Plekhanov et al., 2023). The key question is not simply whether firms advance in green and digital domains separately, but whether they can translate parallel adaptation into organizational integration.

This issue is especially acute for small and medium-sized enterprises (SMEs). Compared with large corporations, SMEs typically operate with thinner managerial bandwidth, weaker data infrastructure, tighter financing conditions, and more limited technical specialization.

Recent OECD work further shows that SME decarbonization policy increasingly focuses on awareness-raising, investment support, emissions monitoring, and sustainability reporting requirements, while digital innovation, AI, and related tools are becoming relevant for the twin transition, sustainability data generation, verification, and SME sustainable finance (Aklilu et al., 2025; OECD, 2026a; OECD, 2026c).

For a business and economics audience, the Eskişehir case examined here is analytically valuable because it allows the twin transition to be examined not as an abstract policy slogan, but as a concrete problem of capability formation under export pressure. In such settings, firms are asked to comply, invest, document, and coordinate simultaneously. Whether they succeed depends less on formal awareness alone than on the organizational depth with which green and digital demands can be combined.

The twin-transition debate is therefore not merely about technological or environmental modernization in isolation. It is also about whether firms can build a form of organizational coherence that allows compliance, performance measurement, and strategic adaptation to reinforce rather than undermine one another. This issue is especially salient for export-oriented SMEs, which often face tight margins and limited room for trial-and-error adjustment.

This article examines these dynamics in Eskişehir, an export-oriented manufacturing ecosystem in Türkiye. The case is not presented as statistically representative of the whole country; instead, it is treated as a bounded and analytically revealing setting in which broader SME bottlenecks can be observed. The ecosystem combines exposure to European value chains with local support for environmental and digital transition, making it a useful setting for examining whether awareness of twin-transition pressures translates into integrated organizational capability.

The central research question is: To what extent do green transition and digital transformation develop as connected rather than merely parallel capabilities in SME governance structures within an institutional-pressure context, and what does the observed degree of integration reveal about broader maturity gaps facing export-oriented SMEs? The article makes three contributions. First, it offers a joint assessment of green maturity, digital capability, and a direct indicator of their organizational integration. Second, it introduces the concept of structural attenuation to describe a cross-sectional maturity gradient across awareness-, implementation-, and integration-intensive indicator classes ordered by increasing organizational complexity. Third, it interprets the case as a local manifestation of wider SME constraints without overstating national representativeness.

2. Literature Review

2.1. Green transition as environmental governance

Green transition is no longer simply a matter of regulatory compliance. It increasingly refers to the incorporation of environmental performance into managerial systems, supplier governance, investment planning, and strategic decision-making. Porter and van der Linde (1995) challenged the assumption that regulation only imposes costs, while Hart (1995) showed that environmentally grounded capabilities may become sources of strategic advantage. Later studies connected this argument to sustainability reporting, carbon disclosure, and environmental performance management (Kolk, 2008; Delmas et al., 2015; Busch & Lewandowski, 2018). Together, this work suggests that environmental adaptation can support legitimacy, resilience, and competitiveness.

In practice, however, environmental governance depends on calculation, traceability, and coordination. Carbon inventories, energy monitoring systems, life-cycle analysis, supplier assessments, and sustainability reports all require comparable metrics and routinized information flows. This is particularly demanding for SMEs, which often lack specialized staff, analytical capacity, and the investment resources needed for more systematic environmental management (OECD, 2022; OECD, 2025). The central issue, then, is not simply whether SMEs recognize the importance of the green transition, but whether they can convert external pressure into meaningful operational change.

2.2. Digital transformation as organizational capability

The digital transformation literature has likewise moved beyond simple technology adoption. Bharadwaj et al. (2013) frame digital business strategy as a driver of new value creation, while Vial (2019) treats digital transformation as structural, strategic, and organizational change. Westerman et al. (2014) and Kane et al. (2015) further link digital maturity to organizational performance, suggesting that technologies matter because they alter routines, coordination mechanisms, and decision processes.

For firms exposed to sustainability-related market and regulatory pressure, digital transformation cannot be understood as a generic modernization agenda. A firm may use digital tools in production planning or inventory control and still remain weak in environmental governance if emissions, energy, supplier, and product data are not integrated into those systems. In export-oriented manufacturing settings, digital capability therefore becomes part of compliance, traceability, and value-chain positioning rather than a stand-alone technical issue.

For this reason, the present article does not equate digitalization with technological sophistication alone. Its concern is whether digital infrastructure becomes consequential for sustainability-related governance. The same logic applies in the opposite direction: environmental ambition has limited strategic value if it cannot be translated into traceable, comparable, and decision-relevant information within the firm.

2.3. Twin transition and the integration problem

The idea of twin transition assumes that digital tools can enable sustainability through monitoring, optimization, reporting, and governance integration. In principle, the relationship is mutually reinforcing: sustainability requirements create demand for better data systems, while digitalization can improve environmental visibility and control. Yet the literature suggests that this relationship is more difficult in practice than in policy discourse. Bocken and Geradts (2020) show that sustainable business model innovation is often blocked by organizational barriers. George et al. (2021) and Plekhanov et al. (2023) likewise emphasize that transformation depends not only on technology uptake, but also on alignment across structures, routines, and managerial logics.

Recent literature has sharpened this integration problem. Christmann et al. (2024) conceptualize twin transformation as an integrated interplay between digital and sustainability transformation, while Breiter et al. (2024) translate this logic into a capability maturity model built around dynamic capabilities. For SMEs specifically, Burinskienė and Nalivaikė (2024) propose an assessment framework for digital and sustainable transformations, and European Commission and Technopolis Group (2024) document practical drivers and constraints in SME twin transition contexts. These studies support the present article's focus on whether green and digital practices become organizationally connected rather than merely co-present.

This distinction matters because the twin transition can be overstated if it is inferred from the mere coexistence of environmental and digital initiatives. Simultaneous movement in two domains may still conceal organizational fragmentation. Firms may pursue environmental compliance and digital modernization at the same time while relying on separate budgets, separate routines, and disconnected information systems. The empirical problem is therefore one of organizational coupling, not simply co-presence. This problem is especially acute in SMEs, where overlapping pressures often exceed internal capacity for synthesis.

2.4. SMEs and globally shared transformation bottlenecks

The broader international literature shows remarkable continuity in the obstacles SMEs face. OECD evidence points to persistent weaknesses in digital adoption linked to infrastructure, cost, skills, and time constraints (OECD, 2021; Bianchini & Lasheras Sancho, 2025). OECD work on sustainable finance finds parallel difficulties in the green transition, including limited access to finance, weak sustainability-data capability, and difficulty preparing credible transition plans (OECD, 2022; OECD, 2025). World Bank and European Investment Bank (EIB) evidence reinforces this picture by linking SME transformation barriers to finance, skills, innovation scaling, and structural fragmentation (World Bank, 2022; EIB, 2026).

These patterns suggest that green and digital weaknesses should not be treated as isolated deficits. From a business and economics perspective, they influence cost structures, productivity, investment priorities, export readiness, and credibility within international value chains. A regionally bounded case can therefore be analytically useful if it shows how such widely documented constraints are configured and experienced within a specific production environment.

2.5. Research gap

Three gaps follow from this literature. First, green-transition maturity and digital-transformation capacity are still rarely assessed within a single empirical design. Second, the link between domain-level progress and actual organizational integration remains under-operationalized; the literature often discusses the twin transition conceptually without measuring whether environmental and digital developments become connected in routines, data systems, and decision structures. Third, although SME constraints are well known, fewer studies show how those constraints are distributed across awareness-, implementation-, and integration-intensive indicator classes within export-oriented industrial ecosystems.

This helps clarify the article's contribution to the SME literature. Many studies identify finance, skills, and infrastructure as constraints, but fewer show how those constraints appear inside the firm as a patterned maturity structure. By tracing where progress is relatively stronger and where it becomes fragile, the study makes the bottleneck more visible and therefore more actionable.

This article addresses these gaps by assessing green maturity, digital capability, and a direct indicator of organizational integration within the same study. Its contribution lies not in claiming to discover SME constraints for the first time, but in showing how institutional pressure is filtered through organizational capacity and where transformation weakens most clearly.

The present study responds to that problem by using a maturity-assessment design that keeps the analysis close to firm-level organizational realities. Instead of assuming that transformation is either present or absent, it examines where maturity appears stronger or weaker across indicator classes and whether the descriptive gap is larger for items requiring cross-domain integration. This cross-sectional comparison is central to the argument developed below.

3. Theoretical Framing and Research Expectations

3.1. Institutional pressure, absorptive capacity, and dynamic capabilities

This article is positioned at the intersection of institutional theory, absorptive capacity, and dynamic capabilities. Institutional theory provides an interpretative lens for understanding coercive, normative, and mimetic pressures that define legitimate organizational behavior (DiMaggio & Powell, 1983). In the present context, instruments such as CBAM (Regulation (EU) 2023/956), CSRD (Directive (EU) 2022/2464), and the DPP framework under the Ecodesign for Sustainable Products Regulation act as strong coercive pressures because they increasingly specify what counts as credible environmental performance, traceability, and future-ready governance (European Commission, 2019; European Commission, 2020; European Union, 2022, 2023, 2024). For export-oriented SMEs, these pressures affect not only compliance, but also market access and buyer expectations.

Yet institutional pressure does not automatically produce deep organizational transformation. Meyer and Rowan (1977) show that organizations may respond symbolically by adopting the language and visible signs of conformity without fundamentally changing internal routines. This distinction matters in the twin-transition context, where firms may show awareness of carbon accounting, sustainability reporting, or digital-product requirements without building the systems needed to operationalize them.

Absorptive capacity adds a second layer to this interpretation. Cohen and Levinthal (1990) define absorptive capacity as the ability to identify, assimilate, and exploit external knowledge, while Zahra and George (2002) distinguish between potential and realized absorptive capacity. Applied here, the implication is that awareness of regulatory change, digital tools, or sustainability expectations should not be confused with the ability to translate such awareness into routines, measurable outcomes, or cross-functional integration.

Dynamic capabilities theory extends this logic by focusing on how firms sense change, seize opportunities, and reconfigure resources and structures in response (Teece, 2007). In SME settings, sensing may occur relatively early, and seizing may appear through selective investments or procedural changes. Reconfiguration, however, is more demanding because it requires shared data systems, managerial alignment, and organizational redesign. Taken together, these perspectives suggest that institutional pressure may trigger attention, but the depth of transformation depends on whether firms possess the absorptive and dynamic capacities needed to convert external demands into integrated capability.

3.2. Structural attenuation and integration bottlenecks

Building on this framework, the study introduces the concept of structural attenuation to describe a cross-sectional maturity gradient across indicator classes ordered by increasing organizational complexity, from awareness-intensive indicators to implementation- and integration-intensive indicators. The term does not denote within-firm decline over time or establish a temporal transition path. Rather, it identifies a pattern in which lower observed maturity coincides with stronger demands for cross-functional coordination, formalized data infrastructure, investment logic, and redesign of organizational routines.

Structural attenuation therefore refers to a patterned cross-sectional difference in maturity across analytically ordered indicator classes. Awareness-oriented indicators may score relatively higher because firms can absorb signals and acknowledge emerging pressures without immediately changing core routines. Implementation-oriented indicators are more demanding because they require operational follow-through and budget allocation. Integration-intensive indicators impose the greatest organizational demands because they require firms to connect environmental and digital developments across governance systems, data architecture, and decision routines. These labels capture the dominant capability demand of each item; they are neither mutually exclusive content categories nor evidence of longitudinal progression by individual firms.

The study also uses the notion of an integration bottleneck. This bottleneck is indicated when firms show some progress in the two multi-item green and digital domains while the single-item S20 integration signal is descriptively lower at the point where the domains must become organizationally connected. In such cases, the pattern is consistent with difficulty in converting parallel developments into an integrated organizational architecture; it should not be read as a measured within-firm transition sequence.

As operationalized in this article, regulatory pressure is treated as an upper-level interpretative context, green-transition maturity and digital-transformation capacity as parallel organizational domains, and their organizational articulation as the mechanism through which the twin transition becomes practically meaningful. This framing makes it possible to move beyond a binary question of whether firms are transforming and instead ask where the transition begins to stall.

This way of framing the problem also helps explain why the study relies on research expectations rather than formal causal hypotheses. The purpose is to interpret a maturity structure, not to estimate a universal law. The analysis therefore remains attentive to pattern, sequence, and organizational depth rather than to isolated coefficient significance. Figure 1 summarizes the resulting operational

framework and the relationship among institutional pressure, the two maturity domains, and their organizational integration.

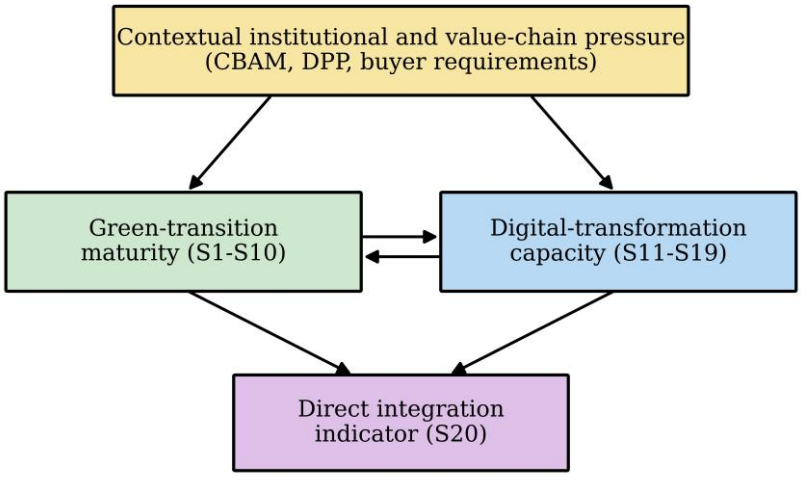


Figure 1. Operationalized Twin Transition Integration Framework

Source: Author's elaboration.

3.3. Research expectations

Because the study follows a maturity-assessment design rather than an inferential hypothesis-testing framework, it formulates research expectations instead of formal hypotheses. These expectations are derived from literature, but they do not predetermine the empirical outcome; rather, they guide the interpretation of how institutional pressure is translated into green, digital, and integrative responses within an export-oriented SME ecosystem.

RE1. Within an institutional-pressure context, awareness-related indicators are expected to display relatively stronger maturity than implementation- and integration-related indicators, because awareness can emerge through early compliance-oriented responses, whereas implementation and integration typically require deeper organizational restructuring, stronger coordination, and greater resource commitment (Meyer & Rowan, 1977; Zahra & George, 2002).

RE2. Green and digital domain scores may show comparable or partially convergent maturity patterns; however, the integration dimension is expected to remain more fragile, reflecting the possibility that progress in parallel domains does not automatically translate into cross-domain organizational synthesis (George et al., 2021; Plekhanov et al., 2023).

RE3. The weakest maturity levels are expected to appear in indicators that depend on integrated data systems, financial justification, and cross-functional coordination, since these capabilities are especially difficult to build in SMEs operating under managerial, financial, and skill constraints (OECD, 2022; OECD, 2025).

RE4. The empirical pattern is expected to broadly resonate with internationally documented SME bottlenecks related to finance, skills, infrastructure, and organizational capacity, while also revealing how these constraints are differentially expressed across awareness-, implementation-, and integration-intensive indicator classes within the studied ecosystem (OECD, 2021; World Bank, 2022; EIB, 2026; Pissareva et al., 2025; OECD, 2026b).

4. Methodology

4.1. Research design and analytical orientation

This study adopts a quantitative, cross-sectional maturity-assessment design. Its purpose is not to estimate a classical causal model or a within-firm temporal sequence, but to compare green-transition and digital-transformation maturity across analytically ordered indicator classes within export-oriented SMEs. A maturity-based approach is appropriate because the analytical concern is not only whether firms report isolated practices, but whether indicators dominated by awareness, implementation, and more demanding forms of organizational integration display different descriptive maturity levels (Schumacher et al., 2016; Bai et al., 2017).

4.2. Case selection and sample

Eskişehir was selected as a purposive and analytically bounded case rather than as a statistically representative sample of all Turkish SMEs. The ecosystem was chosen because of its export orientation, manufacturing concentration, exposure to European value chains, and the presence of local support related to sustainability and digital transformation. This logic is consistent with case-selection approaches that prioritize analytical visibility and theoretical relevance over statistical representativeness (Yin, 2018).

The empirical setting is composed predominantly of SMEs operating in machinery, metal processing, automotive supply, and defense-related production. These firms face a combination of regulatory exposure, buyer-driven compliance expectations, and capability-related adjustment pressures. Data were collected through a structured survey administered to firms in this ecosystem. A total of 73 firms participated, and all responses were anonymized.

The empirical dataset was derived from a needs-analysis survey conducted in January 2026 within the 'Twin Transition for Resilient SMEs' (TWINSME) project implemented by the Eskişehir Chamber of Industry under the Türkiye–EU Business Dialogue II (TEBD-II) programme. The original project report was published in February 2026 and describes the survey as a 20-item maturity inventory designed to assess green transformation maturity in relation to energy, carbon and resource efficiency and digital transformation maturity in relation to data, automation and digital management (Eskişehir Chamber of Industry, 2026). The final analytical dataset used in this article consists of 73 valid firm-level responses. Information on the total number of contacted firms, formal response rate, firm-size distribution and individual respondent positions was not available in the anonymized analytical dataset; this limitation is therefore acknowledged explicitly.

4.3. Survey instrument and maturity architecture

The survey consists of 20 ordered-maturity items organized into three analytical components:

- Green Transition (S1–S10);
- Digital Transformation (S11–S19);
- Twin Transition Integration Indicator (S20).

Seventeen items use a 0–4 ordinal response range, whereas S9 (green finance), S15 (Digital Product Passport readiness), and S20 (twin-transition integration) use 0–3 categories because their original project response ladders contained four substantively ordered stages. Across both formats, the categories distinguish non-adoption or no knowledge, early awareness or elementary practice, partial implementation, and progressively more systematic implementation or formalization. Item-specific normalization is therefore used before aggregation.

The 20-item inventory was originally developed for the TWINSME needs-analysis project implemented by the Eskişehir Chamber of Industry. The project report defines the intended content domains as green-transition maturity in energy, carbon, and resource efficiency and digital-transformation maturity in data, automation, and digital management (Eskişehir Chamber of Industry, 2026). For the present article, all 20 project items were retained rather than selected after inspection of the results and were

mapped to Green Transition (S1–S10), Digital Transformation (S11–S19), and the direct Twin Transition Integration Indicator (S20). The item set is therefore formative: the indicators provide complementary content coverage and are not assumed to be interchangeable manifestations of one latent trait.

Content validation for this article consisted of a documentary and analytical content review rather than reflective-scale validation. The project purpose, the complete item wording, and the ordered response ladders were checked against the operational domains represented in maturity-model and composite-indicator research (Schumacher et al., 2016; Bai et al., 2017; Nardo et al., 2005; OECD et al., 2008). Each response ladder was also examined for monotonic progression from absence or awareness to implementation and formalization, and the item-to-stage mapping was made explicit in Table A1 (Appendix A) and Appendices A1–A3.

The project records available for this study do not document a separate formal expert-panel content-validity index, cognitive pre-test, or pilot sample before field administration; accordingly, none is claimed. The instrument should be interpreted as a project-based formative diagnostic whose present content-validity argument rests on documented domain coverage, ordered response logic, and transparent disclosure of all items. Independent expert validation and pilot testing remain priorities for future scale-development research.

A particularly important design feature concerns the treatment of integration. In the present study, integration is not modeled as a fully multi-item reflective construct but is instead captured through a direct organizational integration indicator (S20). This choice reflects the exploratory and maturity-oriented purpose of the study: rather than assuming that green and digital alignment is already institutionally consolidated in SMEs, the instrument measures whether firms report a recognizable degree of cross-domain organizational connection. For this reason, the integration dimension should be interpreted as an indicator of organizational articulation rather than as a fully elaborated latent scale. The complete response ladders are reproduced in Appendix A, and their analytical stage allocation is reported in Table A1 (Appendix A).

This distinction is methodologically important. The study does not claim that a single item can exhaust the multidimensional reality of integration. Rather, it uses S20 as a focused indicator of whether firms have begun to connect environmental and digital practices within managerial routines and organizational systems. This allows the analysis to test whether domain-level progress is accompanied by a corresponding degree of organizational synthesis, which is central to the twin-transition argument developed in the article.

4.4. Item-level scoring and normalization

For each item i, a weighted arithmetic mean was first calculated as:

$$\overline{X}_i = \frac{\sum_{k=0}^{m_i} x_k f_k}{N} \quad (1)$$

where:

- $\overline{X}_i$ = weighted arithmetic mean for item i
- x_k = ordinal score assigned to category k
- f_k = frequency of firms selecting category k
- m_i = maximum attainable score for item i
- N = total number of firms in the sample

Because not all items shared the same maximum score, the arithmetic mean was converted into a normalized maturity score on a 0–100 scale:

$$M_i = \frac{\overline{X}_i}{m_i} \times 100 \quad (2)$$

where:

- M_i = normalized maturity score for item i
- $\overline{X}_i$ = weighted arithmetic mean for item i
- m_i = maximum attainable score for item i

This transformation makes differently scaled items directly comparable and improves interpretability across the full instrument. The procedure follows standard practices used in composite indicator construction and readiness assessment (Nardo et al., 2005; OECD et al., 2008).

4.5. Dispersion and structural fragility

To capture heterogeneity across firms, the standard deviation for each item was calculated as:

$$SD_i = \sqrt{\frac{\sum_{k=0}^{m_i} f_k(x_k - \overline{X}_i)^2}{N}} \quad (3)$$

where:

- SD_i = standard deviation for item i
- f_k = frequency associated with category k
- x_k = ordinal score of category k
- $\overline{X}_i$ = weighted arithmetic mean for item i
- N = total number of firms

A high standard deviation indicates stronger dispersion across firms and, therefore, greater unevenness in the maturity profile. A low standard deviation combined with low maturity, by contrast, suggests broadly shared weakness among sampled firms rather than a polarized distribution. This distinction matters because low average maturity may conceal two different patterns: scattered experimentation among a few firms or broad underdevelopment among the participating firms.

Because the instrument contains both 0–4 and 0–3 items, dispersion is also reported as a standardized dispersion index:

$$D_i = \frac{SD_i}{m_i} \times 100 \quad (4)$$

where D_i denotes standardized dispersion for an item, SD_i denotes its item-level standard deviation, and m_i denotes its maximum attainable score. This transformation makes dispersion values comparable across response ranges.

In addition, a low-maturity concentration ratio was calculated for each item to show the proportion of firms concentrated in the two lowest maturity categories:

$$HR_i = \frac{f_{0i} + f_{1i}}{N} \times 100 \quad (5)$$

where:

- HR_i = low-maturity concentration ratio for item i
- f_{0i} = number of firms in the lowest category
- f_{1i} = number of firms in the second-lowest category
- N = total number of firms

The baseline low-maturity concentration ratio has a substantive ordinal interpretation rather than an equal-scale-fraction interpretation. For every item, category 0 denotes absence, non-adoption, or no knowledge, while category 1 denotes awareness, information search, planning, or an elementary practice. The two categories therefore represent the same early-maturity stage across the instrument, even though categories 0–1 span 25% of the 0–4 scale and 33.3% of the 0–3 scale.

A scale-range sensitivity check was nevertheless conducted for S9, S15, and S20. A common cut-off at 25% of each item's maximum score retains categories 0–1 for 0–4 items but only category 0 for 0–3 items. As reported in Table C2 (Appendix C), the short-scale estimates decrease from 82.2–84.9% to 47.9–53.4%, as expected when early awareness is excluded, yet approximately one-half of firms still occupy the absolute lowest category. The baseline ratio is retained because it identifies the substantively common stage of non-adoption plus early awareness; it is not interpreted as an equal fraction of each numerical range.

4.6. Composite domain indices

To summarize the maturity profile of the main analytical components, composite indices were constructed by averaging normalized item scores within each component:

$$CI_d = \frac{1}{n_d}\sum_{i=1}^{n_d} M_i \quad (6)$$

where:

- CI_d = composite index for domain d
- n_d = number of items included in domain d
- M_i = normalized maturity score of item i

Using this approach, the study reports:

- Green Transition Index
- Digital Transformation Index
- Single-Item Integration Signal

The use of transparent arithmetic aggregation is consistent with the literature on composite readiness and maturity measures, provided that the construction logic is made explicit and remains substantively interpretable (Nardo et al., 2005; OECD et al., 2008). At the same time, the S20 integration value should be read with appropriate caution because it is a single-item signal rather than a multi-item domain scale. For that reason, the analysis treats it primarily as focused evidence of organizational articulation rather than as a fully symmetric domain construct.

4.7. Attenuation and bottleneck coefficients

To compare maturity across analytically ordered indicator classes, two descriptive attenuation coefficients were defined. The awareness-intensive score A is the arithmetic mean of S1, S2, S11, and S16; the implementation-intensive score I is the mean of S3, S4, S5, S6, S12, S13, S17, and S18; and the integration-intensive class score G is the mean of S7, S8, S9, S10, S14, S15, S19, and S20. This produces the reported class values of 38.6%, 30.8%, and 22.6%, respectively. The labels identify the dominant organizational demand represented by each item and are used for cross-sectional comparison; they do not imply mutually exclusive content or longitudinal progression by individual firms.

The first coefficient measures the descriptive difference in maturity between the awareness-intensive and implementation-intensive indicator classes:

$$\Delta_1 = I - A \quad (7)$$

where:

- Δ_1 = attenuation between awareness and implementation
- A = average maturity score for awareness-related items
- I = average maturity score for implementation-related items

The second coefficient measures the descriptive difference in maturity between the implementation-intensive and integration-intensive indicator classes:

$$\Delta_2 = G - I \quad (8)$$

where:

- Δ_2 = attenuation between implementation and integration
- I = average maturity score for implementation-related items
- G = integration-related score

Using the reported rounded class scores, $\Delta_1 = 30.8 - 38.6 = -7.8$ pp and $\Delta_2 = 22.6 - 30.8 = -8.2$ pp; the difference in magnitude is 0.4 pp. A pattern in which Δ_2 is more negative than Δ_1 indicates that the cross-sectional maturity gradient is only slightly steeper between implementation-intensive and integration-intensive indicator classes. This descriptive pattern is what the article conceptualizes as structural attenuation; it is not evidence of temporal decline within individual firms.

The study also uses the integration bottleneck coefficient to compare the single-item S20 integration signal with the green and digital component scores:

$$B_d = \frac{CI_d - S_{20}}{CI_d} \tag{9}$$

where:

- B_d = integration bottleneck coefficient for domain d
- CI_d = composite score of the green or digital component
- S20 = single-item organizational integration signal

Higher values indicate a larger proportional descriptive gap between a multi-item domain score and the single-item S20 integration signal. The coefficient should therefore be interpreted as a transparent comparison of differently constructed indicators, not as an inferential effect estimate or as evidence that domain maturity has been converted over time.

4.8. Robustness checks

To test whether the results depended on a single category-scoring rule, three category-level transformations were applied. For each item and category, the normalized category position equals the category score divided by the item's maximum score. Linear scoring preserves proportional distance, convex scoring gives greater weight to advanced maturity and penalizes concentration at low stages, and threshold-sensitive scoring records whether a response reaches at least one-half of the available item range. The transformations are defined as follows:

$$z_{ik} = \frac{x_k}{m_i}; \quad g_L(z) = z; \quad g_C(z) = z^2; \quad g_T(z) = \begin{cases} 1, & z \geq 0.50 \\ 0, & z < 0.50 \end{cases} \tag{10}$$

For each specification, the transformed category values are frequency-weighted within each item and multiplied by 100. Item scores are then averaged with equal item weights within the green and digital components; S20 remains the single-item organizational integration signal and is transformed directly under the same category-level rule. All items contain 73 valid responses, so the same denominator is used throughout and no participation adjustment is required.

Table C1 (Appendix C) reports the results. The linear specification yields 29.4% green maturity, 29.3% digital maturity, and a 24.2% S20 integration signal. Convex scoring yields 18.1%, 16.9%, and 13.2%, while threshold-sensitive scoring yields 31.9%, 32.4%, and 17.8%, respectively. Absolute levels change in the direction implied by each transformation, but the single-item integration signal remains descriptively lower than both multi-item domain scores under every specification. Table C2 separately reports the response-range sensitivity of the low-maturity concentration ratio.

These checks do not eliminate the limitations of a formative, single-case maturity assessment, but they show that the central integration gap is not an artifact of the baseline linear coding rule. The scale-range check also identifies where low-maturity concentration values require a substantive rather than purely proportional interpretation.

4.9. Methodological limitations

The study has several limitations. First, the case is regionally bounded and therefore does not support claims of statistical representativeness for all Turkish SMEs. Its broader relevance lies in analytical generalizability rather than statistical extrapolation. The value of the case rests on whether the observed pattern converges with constraints widely documented in international SME literature (Yin, 2018; OECD, 2022; OECD, 2025).

Second, the study is cross-sectional and therefore cannot track how maturity evolves. It captures the current configuration of awareness, implementation, and integration, but not the temporal sequence through which firms move across stages.

Third, the analysis relies on self-reported survey data. As in many firm-level maturity assessments, this introduces some risk of reporting bias, perceptual inflation, or uneven interpretation of categories across respondents.

Fourth, the integration component is measured through a direct single indicator rather than a multi-item scale. This means that the study offers a focused signal of cross-domain organizational articulation, not an exhaustive measurement model. Fifth, the available project records do not document a separate formal expert-panel validation, cognitive pre-test, or pilot sample for the original inventory. These limitations restrict psychometric claims and should guide future expert-validation, pilot-testing, and multi-item scale-development work.

Even with these limitations, the study remains analytically useful because it identifies a clear cross-sectional maturity pattern across firms and shows where lower scores are concentrated. Its contribution lies less in universal measurement claims than in illustrating how the observed indicator-class gradient can be interpreted in light of institutional pressure and documented SME capability constraints.

5. Findings

5.1. Overall maturity remains limited across domains

Across the full instrument, none of the 20 indicators exceeds 45% maturity on the normalized scale. Even the relatively strongest items therefore remain within an early or, at most, intermediate stage of development. The evidence does not indicate a mature twin-transition architecture; rather, it points to fragmented, uneven, and only partially institutionalized progress.

The strongest score is observed in S16 (cybersecurity) at 41.1%, followed by S6 (waste management) at 38.4%, S2 (CBAM knowledge) at 38.0%, S11 (digital transformation strategy) at 38.0%, and S1 (carbon footprint accounting) at 37.3%. At the other end of the spectrum, the weakest items are S8 (life-cycle analysis / eco-design) at 19.2%, S19 (digital investment ROI measurement) at 19.5%, S7 (supplier environmental monitoring) at 21.2%, S10 (sustainability reporting) at 21.9%, S5 (renewable energy) at 24.0%, S14 (digital tracking of energy and emission data) at 24.0%, S15 (DPP readiness) at 24.2%, and S20 (twin transition integration) at 24.2%. This distribution suggests that firms respond more easily to visible, compliance-facing, and operationally immediate requirements than to integrated, data-intensive, and strategically coordinated systems.

5.2. Awareness rises faster than institutional deepening

A second pattern concerns the difference between early awareness and deeper organizational institutionalization. Indicators linked directly to current compliance discourse, such as carbon accounting and CBAM knowledge, perform better than those requiring embedded redesign. A similar tendency appears on the digital side: firms show some progress in digital strategy and cybersecurity, but far less in advanced data integration, investment evaluation, and digitally enabled environmental governance. Institutional pressure is interpreted here as operating first as a signaling mechanism: firms recognize the direction of change, but recognition does not automatically translate into durable routines, coordinated implementation, or integrated capability formation.

5.3. Low-maturity concentration reveals structural fragility

Using the baseline substantive definition (categories 0–1), four items exceed 80% low-maturity concentration: S15 (Digital Product Passport readiness) at 84.9%, S8 (life-cycle analysis / eco-design) at 83.6%, S9 (green finance utilization) at 82.2%, and S20 (twin-transition integration) at 82.2%. For the three 0–3 items, the common scale-fraction sensitivity cut-off reported in Table C2 counts only category 0 and yields 47.9–53.4%. Thus, the precise short-scale percentages depend on whether early awareness is included, but the concentration of firms at complete non-adoption remains substantial.

These are not marginal technical issues. They are precisely the areas that require firms to combine multiple capabilities at once—technical knowledge, organizational planning, financial justification, data governance, and coordination across functions. The weakness observed in these indicators therefore signals more than delayed adoption. It points to a deeper form of structural fragility in which firms struggle most when transformation demands synthesis rather than isolated action.

In other words, the bottleneck becomes sharper as the organizational complexity of the required response increases. This pattern is visually reinforced in Figure 2, which maps the relationship between maturity and low-maturity concentration across all indicators.

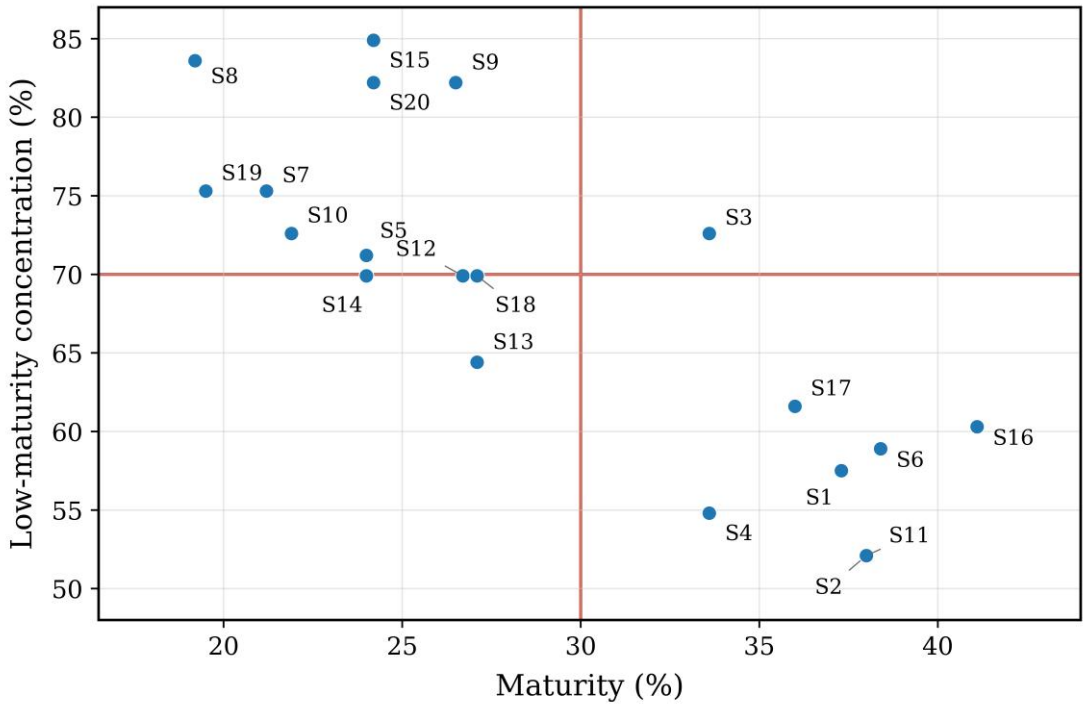


Figure 2. Maturity versus Low-Maturity Concentration Quadrant

Note: The 30% maturity and 70% low-maturity concentration lines are interpretive reference thresholds, not inferential cut-offs; S9, S15, and S20 use 0–3 response ranges.

Source: Author's calculations based on Eskişehir Chamber of Industry (2026).

5.4. Dispersion differentiates uneven adoption from broadly shared weakness

Standardized dispersion values show that not all weaknesses should be interpreted in the same way. S1 (carbon footprint accounting) and S9 (green finance; 0–3 item) display the highest standardized dispersion values, 35.8% and 35.3%, respectively. This suggests a more polarized pattern: some firms have moved forward considerably, while many others remain close to the lowest maturity levels.

By contrast, S20 (twin transition integration) combines low maturity with a comparatively low standardized dispersion (27.2%). The distribution is therefore less polarized than those of S1 and S9 and indicates broadly shared weakness among the participating firms rather than weakness concentrated in only a few observations. Because S20 is a single item, this interpretation is confined to the reported

organizational-articulation signal and is not generalized to a validated multidimensional integration construct.

This distinction matters analytically. Low average maturity may reflect either heterogeneity in adoption or a more broadly shared capability deficit. The S20 distribution is more consistent with the second pattern among the participating firms. Figure 3 reinforces this distinction by plotting maturity against dispersion and separating broadly shared weakness from internally polarized adoption.

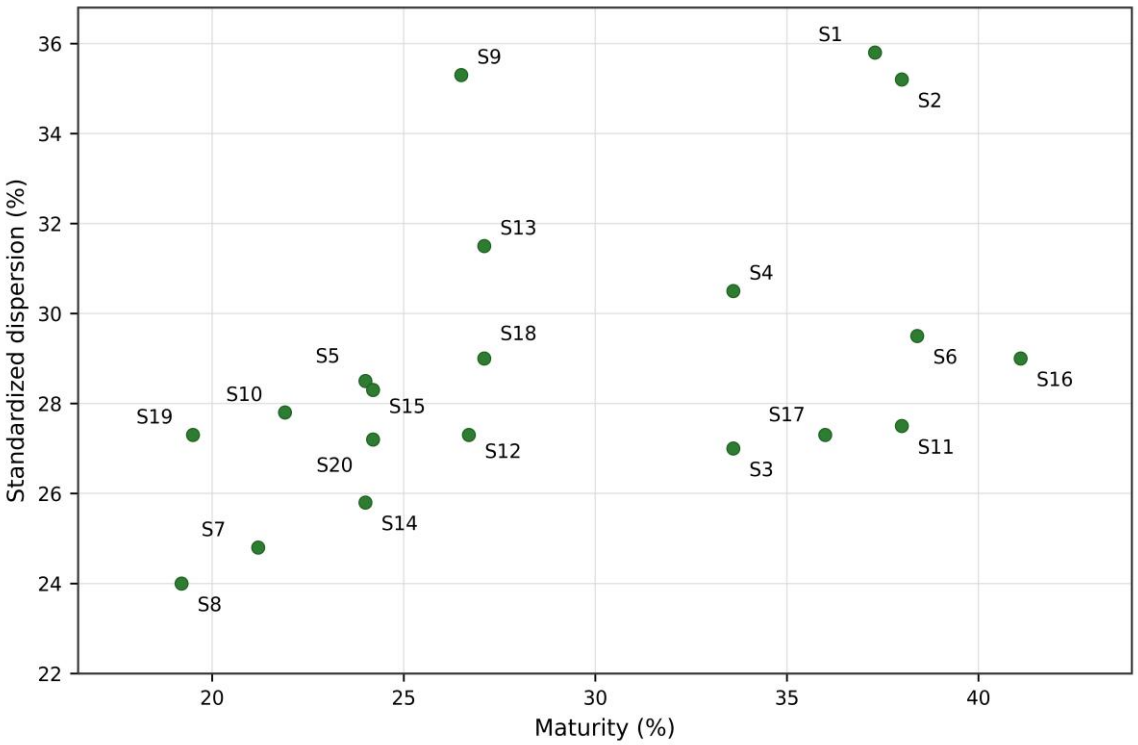


Figure 3. Standardized Dispersion versus Maturity

Source: Author's calculations based on Eskişehir Chamber of Industry (2026).

5.5. Domain-level evidence of an integration bottleneck

The component-level comparison makes the descriptive pattern clear. As shown in Table 1, the Green Transition and Digital Transformation multi-item domains display almost identical mean maturity scores—29.4% and 29.3%, respectively—while the single-item S20 integration signal is 24.2%. Mean low-maturity concentration values follow the same direction: 68.1% for green transition, 67.6% for digital transformation, and 82.2% for S20. These asymmetric constructions are reported together for substantive comparison but are not treated as psychometrically equivalent scales.

Table 1. Domain-Level Comparative Analysis

Analytical component	Mean maturity (%)	Mean low-maturity concentration (%)	Structural interpretation
Green Transition	29.4	68.1	Fragmented implementation
Digital Transformation	29.3	67.6	Operational digitalization
Single-Item Integration Signal (S20)	24.2	82.2	Integration bottleneck

Note: Component means are based on the normalized item scores described in equations (1)–(6).

Source: Author's calculations based on Eskişehir Chamber of Industry (2026).

The descriptive implication is that some progress is visible in the green and digital domains when assessed separately, whereas the single-item signal of organizational synthesis is lower. The cross-

sectional design does not establish that firms moved through these domains sequentially or that earlier domain progress caused later integration outcomes.

Substituting the component values into equation (9), in which S20 denotes the 24.2% single-item integration signal, gives a green-domain coefficient of (29.4 - 24.2) / 29.4 = 0.177 and a digital-domain coefficient of (29.3 - 24.2) / 29.3 = 0.174. The integration-intensive class score G (22.6%) used in equations (7)–(8) is analytically distinct from S20 and is not used in equation (9).

These values indicate a descriptive gap of roughly 17–18% relative to each multi-item domain score. The result is consistent with limited organizational articulation between the green and digital domains, but its magnitude should be interpreted cautiously because the numerator combines a multi-item domain score with the single-item S20 signal.

5.6. Structural attenuation across indicator classes

The indicator-class results also support the concept of structural attenuation. Awareness-intensive items tend to cluster around the upper-30% range, implementation-intensive items score somewhat lower, and integration-intensive items lower still. A slightly larger cross-sectional difference occurs between the implementation-intensive and integration-intensive classes.

This cross-sectional gradient is central to the article's interpretation. The evidence does not establish a temporal decline within firms. Rather, it shows that indicators associated with greater organizational complexity, integration, and resource intensity have lower observed maturity in this sample. Awareness can be stimulated through external pressure and institutional signaling; implementation requires more formal internal follow-through; and integration places the highest demands on organizational coordination.

Figure 4 presents the cross-sectional maturity gradient across analytically ordered indicator classes. It shows that recognition-oriented indicators score higher than indicators requiring integrated organizational transformation; the figure does not depict longitudinal change.

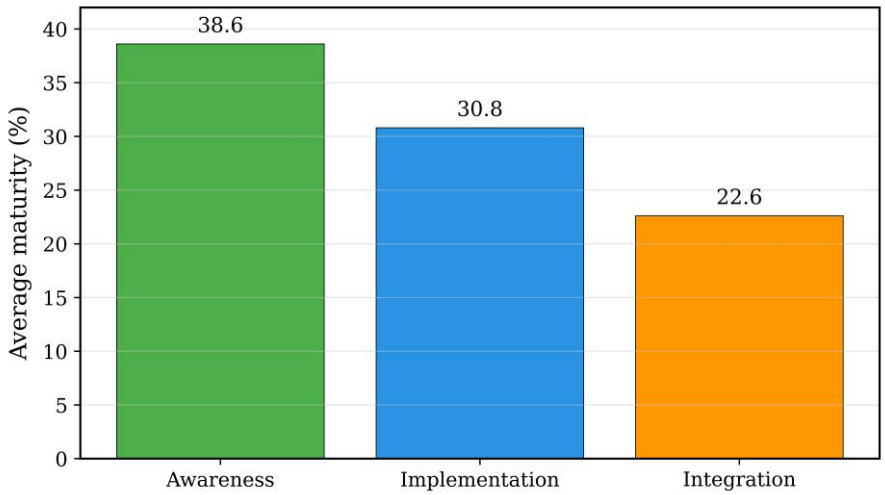


Figure 4. Indicator-Class Attenuation Pattern

Source: Author's calculations based on Eskişehir Chamber of Industry (2026).

5.7. Item-level evidence

The complete item-level profile is reported in Table B1 (Appendix B), the component-level comparison is presented in Table 1, and the most substantively important indicators are summarized in Table 2.

Table 2. Selected Item-Level Indicators

Item	Maturity (%)	Standardized dispersion (%)	Low-maturity concentration (%)	Interpretation
S1 Carbon footprint accounting	37.3	35.8	57.5	Polarized but advancing
S2 CBAM knowledge	38.0	35.2	52.1	Regulatory awareness emerging
S6 Waste management	38.4	29.5	58.9	Operational environmental routine
S11 Digital transformation strategy	38.0	27.5	52.1	Strategic intent emerging
S16 Cybersecurity	41.1	29.0	60.3	Compliance-oriented digital strength
S8 LCA / eco-design	19.2	24.0	83.6	Critical structural weakness
S9 Green finance	26.5	35.3	82.2	Finance-related bottleneck
S15 DPP readiness	24.2	28.3	84.9	Regulatory-preparatory weakness
S19 Digital investment ROI	19.5	27.3	75.3	Weak strategic evaluation capability
S20 Twin transition integration	24.2	27.2	82.2	Broadly shared cross-domain integration weakness

Note: Selected indicators are shown for interpretive emphasis; complete item results appear in Table B1 (Appendix B).

Source: Author's calculations based on Eskişehir Chamber of Industry (2026).

Several contrasts are noteworthy. Carbon footprint accounting and CBAM knowledge are relatively stronger, but also more dispersed, indicating that some firms are moving faster than others in response to current compliance signals. Cybersecurity is the strongest single indicator, which is consistent with the broader tendency of firms to prioritize more immediate digital control and risk-management functions.

By contrast, life-cycle analysis, green finance, DPP readiness, digital investment ROI measurement, and twin integration remain distinctly weak. These items are not only low in maturity but also high in low-maturity concentration, indicating that the weakness is not incidental. They represent precisely the capabilities required to transform fragmented adaptation into more strategic, economically justified, and organizationally connected transformation.

Overall, the empirical pattern can be summarized in three terms: awareness, partial implementation, and weak integration. This triad captures the central maturity structure observed across the sample and anticipates the broader discussion developed in the next section.

6. Discussion

6.1. Institutional-pressure context is associated with attention more readily than integrated transformation

The findings suggest that institutional pressure is already visible within the studied ecosystem, but its organizational effects are uneven. Firms demonstrate a recognizable level of awareness in areas such as carbon accounting, CBAM, digital strategy, and cybersecurity, yet this awareness is not matched by equivalent maturity in implementation-intensive and integration-intensive practices. This supports the

view that the institutional-pressure context is more closely associated with attention, signaling, and initial alignment than with deeper transformation when internal capabilities remain limited. In this sense, the results support RE1 and are consistent with Meyer and Rowan's (1977) argument that organizations often adopt visible forms of conformity before internal routines are fundamentally restructured.

The absorptive-capacity perspective deepens this interpretation. Cohen and Levinthal (1990) and Zahra and George (2002) distinguish between recognizing external knowledge and exploiting it productively. In the present cross-sectional data, relatively higher scores on recognition-oriented indicators and lower scores on indicators requiring stable, cross-functional routines are consistent with this distinction. Institutional pressure may be more readily reflected in attention and signaling than in the capabilities required to absorb and operationalize external demands.

6.2. Parallel progress does not amount to a twin transition

A second major insight is that green and digital maturity do not differ dramatically at the aggregate level, whereas the single-item S20 integration signal is lower. This supports RE2 and indicates that parallel green and digital activity should not automatically be equated with organizational synthesis. In policy discourse, the twin transition is often presented as if green and digital advancement naturally reinforce one another. The evidence here instead shows that a firm may report carbon exposure awareness, cybersecurity investment, or a digital strategy while still remaining weak in life-cycle assessment, DPP readiness, cross-domain data linkage, and investment evaluation.

6.3. The weakest areas cluster around coordination, finance, and data integration

The location of the weakest indicators also matters. Life-cycle analysis, green finance utilization, DPP readiness, digital investment return measurement, and the integration indicator are precisely the areas in which firms must combine technical knowledge, managerial coordination, data infrastructure, and financial justification. This supports RE3 and reinforces the broader literature on SME constraints (OECD, 2021; OECD, 2022; OECD, 2025; World Bank, 2022). These constraints do not remain abstract background conditions; they become visible in the indicators that require organizational synthesis, investment logic, and system-level coordination.

From a business and economics perspective, weakness in these areas is not simply a technical lag. It affects firms' capacity to justify investments, respond to buyer requirements, produce credible sustainability information, and maintain export readiness under increasingly data-intensive market conditions. When firms cannot connect environmental and digital practices, the cost is not only organizational fragmentation. It may also include weaker competitiveness, slower strategic adaptation, and greater vulnerability to exclusion from international value chains.

6.4. Structural attenuation as a cross-sectional organizational pattern

The concept of structural attenuation helps explain the overall pattern. The findings do not point to a binary distinction between firms that are transforming and firms that are not. Instead, they reveal a cross-sectional maturity gradient: awareness-intensive indicators perform relatively better, implementation-intensive indicators are weaker, and integration-intensive performance is weaker still. The pattern is consistent with greater difficulty as organizational demands become more complex, but it does not demonstrate within-firm loss of momentum over time. This interpretation also links the findings to dynamic capabilities theory. In conceptual terms, the lower scores on integration-intensive indicators are consistent with reconfiguration being more demanding than sensing or selective seizing (Teece, 2007), while the cross-sectional design does not directly observe those processes longitudinally.

This helps explain why the article speaks of structural attenuation rather than simple delay. Delay would imply a temporal trajectory that the cross-sectional data cannot establish. Attenuation, as used here, denotes the observed decline in maturity across indicator classes associated with increasing organizational complexity. It identifies a descriptive organizational pattern and a proposition for future longitudinal testing.

6.5. Relation to the broader international SME literature and implications

The findings also speak to RE4. Overall, the empirical pattern broadly resonates with the international literature on SME weaknesses in finance, skills, digital infrastructure, sustainability data, and organizational capacity (OECD, 2021; OECD, 2022; OECD, 2025; World Bank, 2022; EIB, 2026; Pissareva et al., 2025; OECD, 2026b). The value of the present case lies in showing how these bottlenecks are distributed across analytically ordered indicator classes within an export-oriented manufacturing ecosystem. The lower scores on integration-intensive indicators are noteworthy even in a setting exposed to European value chains and supported by local institutions, while the bounded sample does not support national or ecosystem-wide prevalence claims.

The practical implications are straightforward. For managers, compliance awareness is not enough. Firms that remain at the level of carbon-accounting awareness, cybersecurity, or generic digital strategy may still fall short of the capabilities needed for future value-chain participation. Greater emphasis is required on integrated data systems, investment evaluation, life-cycle thinking, supplier traceability, and cross-functional coordination. For policymakers and intermediary institutions, the results indicate that support should move beyond general awareness campaigns and generic digitalization incentives. If the real bottleneck lies in integration, then support mechanisms should prioritize the organizational interfaces between domains: joint green-digital capability programs, DPP readiness, sustainability-data systems, transition-finance access, and training models that combine environmental and digital competencies.

The results also suggest that ecosystem support, while valuable, may be insufficient if it is delivered in fragmented form. Separate programs for digitalization, sustainability, export promotion, or finance may improve awareness in each area without resolving the organizational interfaces between them. This is why integration deserves greater attention from both management practice and public policy.

7. Conclusion

This article examined green-transition maturity, digital-transformation capacity, and their organizational articulation within an institutional-pressure context in an export-oriented SME ecosystem in Türkiye. Drawing on survey evidence from 73 firms, it found uneven maturity across analytically ordered indicator classes. Awareness-intensive indicators perform relatively better, selected implementation-intensive areas show partial progress, and integration-intensive indicators score lower. Carbon-accounting awareness, CBAM knowledge, digital strategy, and cybersecurity appear comparatively stronger, whereas life-cycle analysis, green-finance utilization, DPP readiness, digital investment return measurement, and the single-item S20 integration signal remain fragile.

The central conclusion is that the observed institutional-pressure context is associated with stronger recognition than integrated organizational transformation. Firms are increasingly aware of the direction of regulatory and market change, but they often lack the internal capabilities required to convert that awareness into coordinated, data-intensive, and strategically embedded forms of transformation. The main bottleneck therefore lies not only in limited environmental progress or incomplete digitalization taken separately, but in the organizational capacity needed to connect these domains in ways that are credible, economically justified, and operationally durable.

The article contributes in three ways. It jointly examines green maturity, digital capability, and a direct single-item signal of integration; it introduces structural attenuation as a cross-sectional maturity gradient across indicator classes ordered by increasing organizational complexity; and it interprets the studied ecosystem as a bounded yet analytically revealing setting that makes wider SME constraints visible without claiming national representativeness or temporal progression.

The findings also have practical significance. Managers need more than awareness under increasingly data-intensive compliance regimes; they need investment-appraisal capability, integrated data systems, cross-functional coordination, and supplier-related traceability. Policymakers and intermediary institutions, in turn, should place greater emphasis on the organizational interfaces where green and digital transformation must converge. Without such support, SMEs risk remaining in a state of visible responsiveness but weak integration.

The study has limitations. It is based on a regionally bounded, cross-sectional sample, relies on self-reported firm data, and uses a focused integration indicator rather than a fully elaborated multi-item integration scale. These limitations should be acknowledged when interpreting the results, but they do not diminish the core insight: for export-oriented SMEs, the real challenge of the twin transition is not simply to respond to green and digital pressures, but to build the organizational capacity required to connect them. Future research can extend this contribution through longitudinal, comparative, and scale-development studies.

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Conflicts of Interest

The author declares that there are no conflicts of interest regarding the publication of this paper.

Data Availability

Firm-level responses cannot be deposited publicly because of confidentiality and anonymity commitments made to the participating enterprises. The complete instrument, aggregated item-level results, and calculation specifications underlying the reported analyses are available from the corresponding author upon reasonable request. Any access remains subject to the data-providing institution's confidentiality requirements.

AI Disclosure Statement

The author used OpenAI ChatGPT (GPT-5; accessed September 2026) as a supportive tool for language editing, clarity improvement, formatting assistance, reference organization, revision organization, and code assistance for standard robustness calculations. The tool was not used to generate original research ideas, fabricate data or references, or replace the author's scientific reasoning and interpretation. The author reviewed and approved the final manuscript and takes full responsibility for its content.

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Appendices

Appendix A. Survey Instrument

This appendix presents the structured survey instrument used to assess green-transition maturity, digital-transformation capacity, and their organizational articulation at the firm level. The instrument consists of 20 ordered-maturity items grouped into Green Transition (S1–S10), Digital Transformation (S11–S19), and the single-item Twin Transition Integration signal (S20). Each item was measured through ordered response categories designed to capture progression from non-adoption or low awareness to more systematic implementation and, where applicable, stronger organizational embedding.

Table A1. Allocation of Survey Items to Analytical Indicator Classes

Stage	Items	Analytical rationale
Awareness / compliance-facing	S1, S2, S11, S16	Carbon accounting, CBAM knowledge, digital strategy and cybersecurity are treated as visible compliance-facing or recognition-oriented indicators.
Implementation / operational	S3, S4, S5, S6, S12, S13, S17, S18	These items require operational routines, investment, monitoring, data collection, skills or system use beyond awareness.
Integration-intensive	S7, S8, S9, S10, S14, S15, S19	These items require cross-functional coordination, supplier linkage, finance, product/environmental data or reporting integration.
Single-item integration signal	S20	S20 is interpreted as a focused indicator of green-digital organizational articulation, not as a validated multi-item latent construct.

Source: Author's analytical classification based on the TWINSME instrument.

Note: G = mean of S7, S8, S9, S10, S14, S15, S19, and S20.

Appendix A1. Green Transition Items (S1–S10)

S1. Is carbon footprint accounting conducted?
0 = No implementation
1 = Awareness only
2 = Partial calculation
3 = Scope 1-2 calculation
4 = Scope 1-2-3 regularly calculated

S2. What is the level of knowledge regarding CBAM?
0 = No knowledge
1 = Heard of it
2 = Basic knowledge
3 = Roadmap exists
4 = Affected products identified

S3. Is energy consumption systematically monitored?
0 = No
1 = Invoice-based
2 = Department-based
3 = Digital monitoring
4 = ISO-based management

S4. Have energy-efficiency investments been made?
0 = None
1 = Planning stage
2 = Small-scale investment
3 = Major investment
4 = Continuous improvement approach

S5. Is renewable energy used?
0 = No
1 = Under consideration
2 = Partial use
3 = Major share
4 = Linked to a carbon-neutrality target

S6. What is the level of waste management?
0 = Not systematic
1 = Legal compliance only
2 = Segregation exists
3 = Recovery is measured
4 = Circular-economy approach

S7. Is supplier environmental performance monitored?
0 = No
1 = On the agenda
2 = Partial monitoring
3 = Environmental criteria applied
4 = Sustainable supply-chain approach

S8. Are life-cycle analysis / eco-design practices used?
0 = No
1 = Awareness only
2 = Pilot use
3 = Applied in some products
4 = Fully integrated

S9. Is green finance utilized?
0 = No
1 = Information search
2 = Application submitted
3 = Actively utilized

S10. Is sustainability reporting conducted?
0 = No
1 = Planning stage
2 = Basic reporting

3 = Integrated reporting
4 = GRI-aligned reporting

Appendix A2. Digital Transformation Items (S11–S19)

S11. Is there a digital transformation strategy?
0 = None
1 = Agenda item
2 = Informal approach
3 = Roadmap and KPIs exist
4 = Formal written strategy

S12. What is the level of digital data collection in production?
0 = Manual
1 = Partially digital
2 = Machine-based
3 = Real-time analysis
4 = Fully integrated

S13. What is the ERP/MES usage level?
0 = None
1 = Limited ERP
2 = ERP active
3 = Full digital management
4 = ERP + MES integration

S14. Are energy and emission data digitally tracked?
0 = No
1 = Manual
2 = Spreadsheet-based
3 = Software-supported
4 = Automated integration

S15. What is the level of Digital Product Passport readiness?
0 = No knowledge
1 = Awareness
2 = Regulatory tracking
3 = Pilot implementation

S16. What is the cybersecurity level?
0 = No measure
1 = Basic measures
2 = Policy exists
3 = Regular audits
4 = Systematic framework (e.g. ISO 27001)

S17. What is the level of employee digital competence?
0 = Inadequate
1 = Basic user level
2 = Training provided
3 = Specialist staff available
4 = Continuous learning culture

S18. Is AI / data analytics used?
0 = None
1 = Under consideration
2 = Pilot project
3 = Operational use
4 = Decision-support level

S19. Is the return on digital investment measured?
0 = No
1 = Rough estimation
2 = Project-based
3 = Strategic tracking
4 = KPI-based regular monitoring

Appendix A3. Twin Transition Integration Indicator (S20)

S20. What is the level of integration between green transition and digital transformation?
0 = None
1 = Awareness level
2 = Partial integration
3 = Formal twin-transition strategy

Note: In this study, S20 is treated as a single-item organizational integration signal rather than as a fully elaborated multi-item construct. It is therefore interpreted as focused evidence of whether cross-domain organizational articulation is reported at the firm level.

Appendix B. Item-Level Results

This appendix reports the empirical results generated from the maturity-assessment framework. Table B1 presents item-level normalized maturity, standardized dispersion, and low-maturity concentration, while Table 1 in the main text summarizes the three analytical components.

Table B1. Item-Level Maturity, Standardized Dispersion, and Low-Maturity Concentration

Item	Analytical component	Maturity (%)	Standardized dispersion (%)	Low-maturity concentration (%)	Interpretation
S1	Green Transition	37.3	35.8	57.5	Polarized but advancing
S2	Green Transition	38.0	35.2	52.1	Regulatory awareness emerging
S3	Green Transition	33.6	27.0	72.6	Monitoring capacity still uneven
S4	Green Transition	33.6	30.5	54.8	Investment activity developing
S5	Green Transition	24.0	28.5	71.2	Renewable transition remains limited
S6	Green Transition	38.4	29.5	58.9	Operational environmental routine
S7	Green Transition	21.2	24.8	75.3	Supplier-side sustainability weakness
S8	Green Transition	19.2	24.0	83.6	Critical structural weakness
S9	Green Transition	26.5	35.3	82.2	Finance-related bottleneck
S10	Green Transition	21.9	27.8	72.6	Reporting capability remains weak
S11	Digital Transformation	38.0	27.5	52.1	Strategic intent emerging
S12	Digital Transformation	26.7	27.3	69.9	Production digitalization still partial
S13	Digital Transformation	27.1	31.5	64.4	ERP/MES depth remains uneven
S14	Digital Transformation	24.0	25.8	69.9	Environmental data integration limited

S15	Digital Transformation	24.2	28.3	84.9	Regulatory-preparatory weakness
S16	Digital Transformation	41.1	29.0	60.3	Compliance-oriented digital strength
S17	Digital Transformation	36.0	27.3	61.6	Digital skills improving but incomplete
S18	Digital Transformation	27.1	29.0	69.9	Analytics use remains early-stage
S19	Digital Transformation	19.5	27.3	75.3	Weak strategic evaluation capability
S20	Single-Item Integration Signal	24.2	27.2	82.2	Broadly shared cross-domain integration weakness

Note: Maturity is normalized to 0–100. Standardized dispersion equals the item standard deviation divided by the maximum item score and multiplied by 100. The baseline low-maturity concentration ratio is the share in categories 0–1.

Source: Author's calculations based on Eskişehir Chamber of Industry (2026).

Appendix C. Robustness Note

Table C1 implements the linear, convex, and threshold-sensitive transformations defined in equation (10) and reports the resulting green, digital, and S20 integration values. As expected, absolute score levels vary across transformations, but the single-item integration signal remains descriptively lower than both multi-item domain scores under every specification. Table C2 reports the separate response-range sensitivity check for the three 0–3 items.

Table C1. Robustness Comparison of Alternative Scoring Specifications

Specification	**Green maturity (%)**	**Digital maturity (%)**	**S20 signal (%)**	**Interpretation**
Linear: $g_L(z) = z$	29.4	29.3	24.2	Baseline; integration remains below both domains.
Convex: $g_C(z) = z^2$	18.1	16.9	13.2	Advanced-stage weighting; integration remains lowest.
Threshold: $g_T(z) = 1$ if $z \geq 0.50$; 0 if $z < 0.50$	31.9	32.4	17.8	Mid-point attainment; the integration deficit widens.
Linear excluding S9 and S15	29.7	29.9	24.2	Excluding shorter-range domain items leaves the integration pattern unchanged.

Note: $z_{ik} = x_k/m_i$. Convex and threshold transformations are applied at category level before equal-weighted component aggregation; N = 73 for every item.

Source: Author's calculations from the reported item-frequency distributions.

Table C2. Sensitivity of Low-Maturity Concentration for 0–3 Items

Item	Scale	Baseline: categories 0–1 (%)	Common cut-off: x/m ≤ 0.25 (%)	Interpretation
S9 Green finance	0–3	82.2	53.4	Over half report no utilization; the remainder of the baseline ratio reflects information search.
S15 DPP readiness	0–3	84.9	47.9	Nearly half report no knowledge; the remainder of the baseline ratio reflects awareness only.
S20 Twin-transition integration	0–3	82.2	47.9	Nearly half report no integration; the remainder of the baseline ratio reflects awareness only.

Note: The common scale-fraction cut-off equals categories 0–1 for 0–4 items but category 0 only for 0–3 items. It therefore isolates complete non-adoption in the three shorter-range items.

Source: Author's calculations based on exact frequencies reported by Eskişehir Chamber of Industry (2026).

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