

On a Universal Factory-Oriented Quality Index for Corrugated Board

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Quality assessment of corrugated board in industrial practice is usually based on individual laboratory tests such as the edge-crush test, bending stiffness, or shear-related measurements. While informative, single-test evaluation cannot capture the combined effects of anisotropy, structural degradation, and material efficiency. This editorial highlights the need for a universal, factory-oriented quality index that integrates results from commonly used tests into a single, interpretable scalar. The proposed concept emphasizes normalization with respect to basis weight, aggregation of directional properties, and sensitivity to shear-related damage mechanisms. A general mathematical framework is outlined, demonstrating how mechanical performance, structural integrity, and economic considerations may be combined to support transparent benchmarking and more informed industrial decision-making.

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Motivation and Industrial Context

Corrugated board remains one of the most widely used structural materials in modern packaging systems, combining low mass, recyclability, and sufficient mechanical performance for transport and storage applications (Gaudelas *et al.* 2023). Despite its apparent simplicity, corrugated board is a highly engineered multi-layer composite whose mechanical behavior results from a complex interaction between liners, fluting geometry, bonding quality, moisture sensitivity, and production-induced defects.

From an industrial perspective, quality assessment of corrugated board is traditionally performed using a set of well-established laboratory tests, such as the Edge Crush Test (ECT), bending stiffness tests (BNT), transverse and shear-related tests (TST, SST), and selected compression or stability-oriented procedures. Each of these tests captures a specific physical mechanism governing the performance of corrugated structures. However, they are typically interpreted independently, often leading to fragmented or even contradictory assessments of material quality.

In practice, this fragmentation creates a persistent gap between laboratory characterization and factory-level decision-making. A board grade may exhibit excellent ECT performance while simultaneously showing poor shear integrity or early signs of structural degradation caused by creasing, crushing, or delamination of the fluting. Conversely, lightweight constructions may be mechanically efficient but penalized in traditional assessments simply because of their reduced basis weight. As a result, neither a single test nor a simple pass/fail criterion can reliably represent the overall quality of corrugated board in a universal, comparable manner.

This editorial argues that the time is ripe for introducing a universal, factory-oriented quality index for corrugated board—one that integrates multiple laboratory test outcomes into a single scalar indicator, while remaining interpretable, transparent, and compatible with industrial constraints. Rather than proposing a finalized standard, this contribution aims to outline the conceptual foundations, mathematical structure, and practical motivations for such an index.

Limitations of Single-parameter Quality Assessment

The industrial dominance of ECT as a primary quality indicator is historically justified, as edgewise compression capacity strongly correlates with the stacking strength of corrugated boxes (Popil 2012). Nevertheless, it is now well recognized that ECT alone does not capture several critical failure modes observed in real packaging systems.

Bending stiffness, typically measured in machine and cross directions, governs panel stability, bulging, and load redistribution. Shear-related properties, accessible through tests such as TST or SST, are closely linked to interlayer cooperation and bonding integrity. Importantly, reduced shear stiffness is often associated with irreversible damage mechanisms, including local crushing of the fluting or partial delamination, which may not be reflected in ECT values.

From a production standpoint, this means that two boards with similar ECT values may behave very differently in downstream processes, particularly under dynamic loading (Johst *et al.* 2023; Tworzydło *et al.* 2026), moisture variations, or repeated handling. Moreover, directional anisotropy (MD/CD) further complicates interpretation, as industrial applications rarely load corrugated panels in a single, well-defined direction.

These observations motivate a shift from single-metric evaluation toward multi-criteria synthesis, where different mechanical tests are treated as complementary rather than competing sources of information.

Toward a Universal Scalar Indicator

The central idea advocated here is the construction of a scalar quality index that aggregates the information carried by several laboratory tests into a single numerical value, while preserving the physical meaning of each contributing mechanism. The preliminary framework discussed by Garbowski and Graczyk (2026) was an initial proof-of-concept, demonstrating that the construction of such a universal quality index is not only conceptually justified but also practically feasible.

Let X_i denote the result of the i -th laboratory test, where the set may include, for example:

$$\{X_i\} = \{ECT, BNT_{MD}, BNT_{CD}, TST_{MD}, TST_{CD}, SST\}. \quad (1)$$

To enable meaningful aggregation, three conceptual steps are essential: (A) normalization, ensuring comparability across different board constructions and manufacturers; (B) directional aggregation, accounting for anisotropy between MD and CD; (C) weighted synthesis, reflecting the relative importance of different mechanisms.

A generic normalized variable may be expressed as,

$$\tilde{X}_i = \frac{X_i}{BW^\alpha}, \quad (2)$$

where BW denotes the total basis weight and α is a scaling exponent reflecting the desired notion of material efficiency. The choice $\alpha = 1$ corresponds to performance per unit mass, a particularly attractive concept in lightweight packaging design.

For directional quantities, such as bending or transverse stiffness, an effective scalar can be introduced using a geometric aggregation penalized by anisotropy,

$$X_{\text{eff}} = \sqrt{X_{MD}X_{CD}} \exp\left(-\lambda \left| \ln \frac{X_{MD}}{X_{CD}} \right| \right), \quad (3)$$

where λ controls sensitivity to directional imbalance.

To avoid reliance on external reference values, all normalized quantities may be transformed into standardized variables within a given benchmark set,

$$z_i = \frac{\ln(\tilde{X}_i) - \mu_i}{\sigma_i}, \quad (4)$$

with μ_i and σ_i denoting the mean and standard deviation of $\ln(\tilde{X}_i)$.

Structure of a Factory-oriented Quality Index

Based on the standardized variables z_i , a preliminary form of a universal quality index can be written as a weighted sum,

$$QI = \sum_i w_i z_i, \quad (5)$$

where the weights w_i satisfy $\sum_i w_i = 1$.

This formulation offers several practical advantages. First, it yields a dimensionless scalar that can be directly ranked. Second, the weights can be adapted to specific industrial priorities (e.g., stacking strength, panel stability, or damage tolerance). Third, the contribution of each test remains traceable, ensuring transparency rather than black-box optimization.

An important extension concerns damage-sensitive parameters, particularly shear-related tests. Empirical observations indicate that abnormally low shear stiffness often signals structural degradation that may not be visible in other metrics. To reflect this, a penalty term can be introduced,

$$QI_{\text{dam}} = QI - \kappa \max(0, z_{\text{crit}} - z_{\text{SST}})^p, \quad (6)$$

where z_{crit} defines a threshold for anomalous behavior, κ controls penalty severity, and $p > 1$ ensures nonlinear amplification of severe defects.

Finally, from a factory and supply-chain perspective, quality cannot be fully decoupled from economics. A cost-aware extension may therefore be expressed as,

$$QI_{\text{val}} = QI_{\text{dam}} - \beta z_{C/BW}, \quad (7)$$

where C/BW denotes the cost per unit basis weight, and β reflects economic sensitivity.

Why “factory-oriented”?

The term factory-oriented is used deliberately. The proposed framework is not intended to replace detailed material modeling (Aduke *et al.* 2024) or advanced numerical homogenization (Garbowski and Jarmuszcak 2014a, 2014b). Instead, it aims to bridge laboratory testing and day-to-day industrial decisions.

A factory-oriented index should: (a) operate on routinely measured test results, (b) require no proprietary reference values, (c) allow comparison across suppliers and constructions, (d) reward material efficiency rather than absolute mass, and (e) flag hidden degradation mechanisms early. In this sense, the index acts as a decision support tool, not a theoretical ideal. Its strength lies in its adaptability and interpretability rather than strict optimality.

Outlook and Standardization Potential

The concept outlined here does not prescribe a single, immutable formula. Instead, it defines a framework within which different industries, producers, or research communities can calibrate weights, thresholds, and penalties according to their needs.

Future developments may include: (i) validation against large industrial datasets, (ii) correlation with box compression and field performance, (iii) integration with moisture-dependent testing, and (iv) potential incorporation into quality control standards.

Ultimately, the introduction of a universal, factory-oriented quality index could facilitate more transparent communication between producers, converters, and end users, while promoting lightweight, cost-effective, and mechanically reliable corrugated board solutions. Therefore, rather than asking *which single test defines quality*, the more relevant question may be *how different tests jointly describe the structural health and efficiency of corrugated board*. This editorial suggests that a universal scalar index – carefully normalized, damage-aware, and economically informed – can provide a meaningful answer.

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