Reevaluating Safety Margins in Corrugated Board Packaging

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Safety margins have long been a cornerstone of corrugated board packaging design, serving as a practical buffer against uncertainty in material properties, loading conditions, and environmental exposure. Traditionally, these margins have been expressed as single conservative factors derived from standardized laboratory tests and simplified analytical models. While effective in ensuring robustness, such an approach increasingly reveals its limitations. Modern logistics systems are characterized by strong variability, time-dependent effects, and growing pressure to reduce material consumption. This work argues that classical safety margins should be reconsidered not as fixed scalar values, but as dynamic, context-dependent constructs. A conceptual shift is proposed, moving from static safety factors toward a multidimensional safety landscape that reflects the combined influence of climate, time, geometry, and logistics-specific loading scenarios. Emerging tools in numerical modeling, sensing technologies, and data-driven analysis provide the foundation for this transition. The paper outlines the implications of such reframing for sustainable packaging design and highlights how a more nuanced understanding of safety margins can simultaneously improve reliability and reduce material overdesign.

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Safety Margins as Inherited Conventions

Safety margins in corrugated board packaging did not emerge from first principles alone; they are the result of decades of accumulated engineering practice, empirical calibration, and standardization. The edge crush test, box compression test, and related indices have shaped a design culture in which structural safety is assessed through a limited set of laboratory conditions. Results of such tests have been translated into simplified safety factors (Garbowski 2023a). These factors act as a safeguard against uncertainties that are difficult to model directly, such as material heterogeneity, imperfections introduced during converting, or variability in logistics handling.

Over time, however, safety margins have gradually become transformed from quantified measures of risk into inherited conventions. In many design workflows, their numerical values are rarely questioned. Rather, they have been adjusted mainly through experience rather than through a systematic reassessment of underlying assumptions. As logistics systems become more complex and sustainability targets more stringent, this inherited conservatism begins to carry a tangible cost, particularly under extreme environmental conditions (Garbowski 2023b). Excessive safety margins translate directly into higher board grammage, additional layers, or reinforced geometries that may no longer be justified by actual operating conditions.

These observations do not imply that safety margins are obsolete. On the contrary, they remain essential. What deserves reconsideration is their form. Treating safety as a single scalar number implicitly assumes that uncertainty is uniform, stationary, and independent of context. In reality, none of these assumptions holds for corrugated board packaging operating across diverse climates, transport modes, and storage durations.

The Limits of Classical Safety Factors

The classical safety factor is rooted in static thinking. It assumes a reference load, a reference strength, and a fixed ratio between the two. Such an approach struggles to capture phenomena that evolve in time or space. Corrugated board is a hygroscopic, viscoelastic material whose stiffness and strength are strongly influenced by moisture content and temperature. Under prolonged loading, creep and stress relaxation progressively reduce load-bearing capacity, even if no visible damage occurs.

In addition, real packaging structures rarely conform to idealized boundary conditions. Pallet overhang, uneven support, asymmetric stacking, and local geometric discontinuities such as hand holes or perforations generate localized stress concentrations. These effects may remain invisible in global strength indicators while significantly reducing local safety margins, as already indicated in early studies on edge compression behavior and interflute instability (Popil *et al*. 2012). A single global safety factor is unable to reflect such spatial variability.

Logistics dynamics further complicate the picture, as transport-induced impacts and transient loads may activate damage mechanisms not captured by quasi-static design assumptions (Johst *et al*. 2023). Transport-induced vibrations, shocks, and tilting introduce transient loads whose amplitudes and frequencies depend on route, vehicle type, and handling practices. Classical safety factors, calibrated against quasi-static laboratory tests, implicitly assume that these dynamic effects are either negligible or sufficiently covered by conservatism. As evidence accumulates, it becomes clear that this assumption is not always justified, nor is it necessarily efficient.

From Safety Factor to Safety Landscape

To address these limitations, a conceptual shift is proposed: replacing the notion of a single safety factor with that of a safety landscape. Such as shift aligns with recent developments in smart transport packaging design that emphasize data-informed balancing of safety and material efficiency (Garbowski 2025). In this perspective, safety is no longer represented by one number but by a multidimensional field that becomes defined over time, space, and environmental conditions. Each point in this field corresponds to a local safety margin associated with a specific combination of load, material state, and boundary condition.

In a safety landscape framework, regions of high safety coexist with zones where safety is locally depleted. These zones may evolve over time as moisture accumulates, creep progresses, or loading configurations change. Importantly, local depletion does not necessarily imply imminent global failure. Instead, it highlights areas where design interventions or monitoring efforts should be focused.

Such a representation aligns more closely with the physical behavior of corrugated board packaging, which can be effectively described using homogenized material properties derived from analytical approaches (Garbowski and Jarmuszczak 2014a). It acknowledges that safety margins drift over time rather than remain fixed and that uncertainty is structured rather than uniform. Such a perspective can be quantitatively explored using numerical homogenization techniques (Garbowski and Jarmuszczak 2014b). The safety landscape does not aim to eliminate conservatism but to allocate it more rationally, concentrating material where it contributes most effectively to reliability. This conceptual shift is illustrated in Fig. 1a, where the classical notion of a constant safety factor is contrasted with a multidimensional safety landscape. The temporal evolution of safety margins, including local depletion effects, is schematically shown in Fig. 1b.

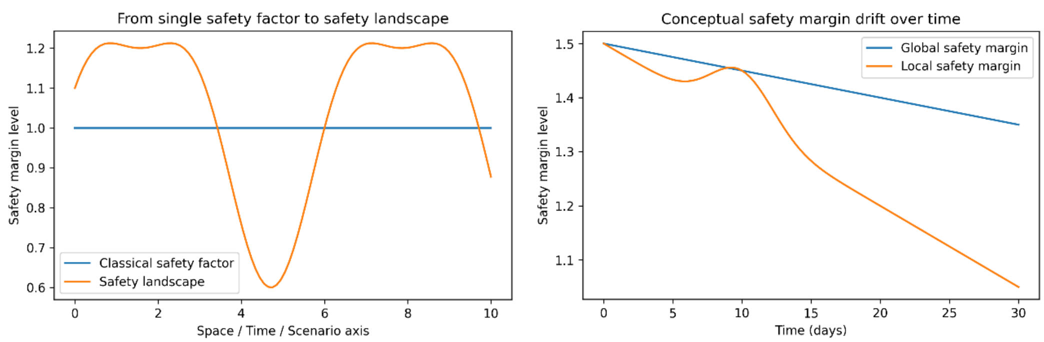

Fig. 1. Safety factors: a) from single safety factor to safety landscape, b) Conceptual safety margin drift over time

Emerging Tools Enabling Reevaluation

The feasibility of this conceptual shift is closely linked to recent advances in modeling and measurement. Numerical models of corrugated board have evolved from purely elastic representations toward formulations that incorporate moisture-dependent properties, viscoelastic effects, and geometric nonlinearity, reflecting the increasing interest in physically characterized biobased corrugated materials (Aduke *et al*. 2024, Gaudelas *et al*. 2023). Reduced-order models and homogenization techniques (Garbowski and Jarmuszczak 2014a,b) make it possible to apply these descriptions at the packaging scale without prohibitive computational cost, even when recycled fibers and modified lignin-based binders introduce additional material variability (Luo *et al*. 2022).

At the same time, miniature sensors capable of recording humidity, temperature, and acceleration during real transport cycles provide unprecedented insight into actual operating conditions. These data streams allow designers to replace assumed worst-case scenarios with statistically representative logistics fingerprints. When combined with numerical models, they enable the construction of safety landscapes grounded in measured reality rather than abstract assumptions.

Data-driven methods further extend these capabilities. Machine learning and clustering techniques can identify recurring patterns in logistics data, reducing the dimensionality of the problem and highlighting dominant risk scenarios. In this context, digital twins of packaging systems do not serve as exact replicas but as adaptive models that update safety estimates as new information becomes available.

Implications for Sustainable Packaging Design

Reframing safety margins has direct implications for sustainability. Overdesign can entail substantial excess material consumption. A safety landscape approach enables targeted optimization, reducing material where safety margins are consistently high and reinforcing only those regions or scenarios that truly govern reliability. Crucially, this does not imply a reduction in safety. By explicitly accounting for degradation mechanisms and context-specific risks, overall reliability can be maintained or even improved. Safety becomes a managed quantity rather than an assumed surplus. Such an approach supports the dual objective of minimizing resource use while maintaining functional performance.

Closing Remarks

This editorial has argued for a reframing of safety margins in corrugated board packaging toward dynamic, context-aware constructs. The proposed concept does not seek to replace existing standards overnight, nor does it prescribe a single new metric. Instead, it offers a way of thinking that aligns more closely with material behavior, logistics reality, and sustainability goals. As packaging systems continue to evolve, the question is no longer whether safety margins are necessary, but how intelligently they are defined and applied. Treating safety as an evolving quantity rather than a fixed constant opens new avenues for research, design, and industrial practice. It invites the community to reconsider what "safe enough" truly means in an era of data-rich, sustainability-driven engineering.

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