Optimization in Structural Design of Corrugated Board: Existing Techniques, Current Gaps, and Future Perspectives

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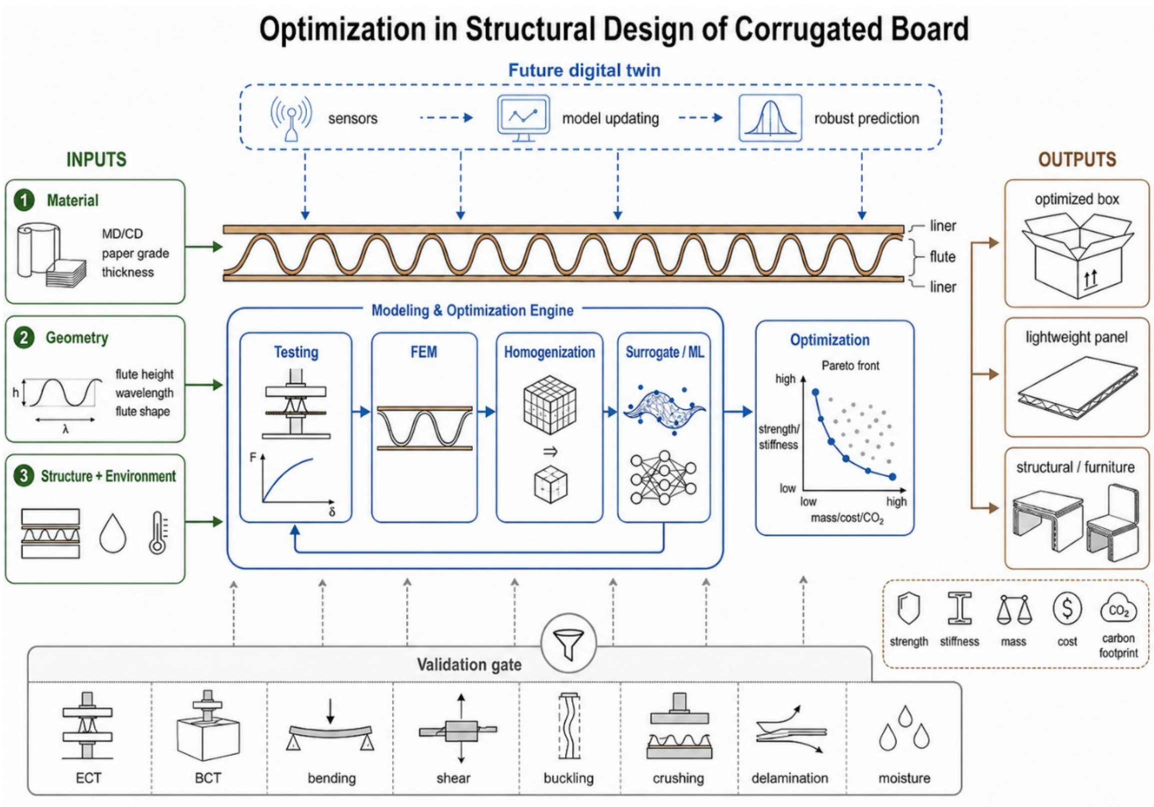
GRAPHICAL ABSTRACT



Optimization in Structural Design of Corrugated Board: Existing Techniques, Current Gaps, and Future Perspectives

Tomasz Garbowski ,[a,*] Julia Graczyk ,[b] and Dawid Karasiewicz [b]

Corrugated board, traditionally used in packaging, is increasingly explored as a structural material for lightweight engineering applications, including furniture, panels, and temporary building components. This transition requires moving beyond empirical design rules toward performance-driven and optimization-based methodologies. This paper presents a critical review of optimization techniques applied to the structural design of corrugated board, with emphasis on the mechanical and numerical foundations required for physically reliable optimization. The reviewed studies were selected from major scientific databases using keywords related to corrugated board, structural optimization, finite element modeling, homogenization, surrogate modeling, machine learning, hygro-mechanical behavior, failure mechanisms, and experimental validation. Unlike earlier reviews focused mainly on industrial optimization practices and algorithms, this review highlights model fidelity, validation hierarchy, moisture sensitivity, local failure, interface damage, and the maturity of data-driven workflows. Analytical models, finite element approaches, homogenization frameworks, reduced-order models, and surrogate-assisted strategies are discussed in terms of their applicability to iterative optimization. Key design variables, including flute geometry, layer configuration, material anisotropy, and environmental conditions, are related to stiffness, strength, stability, ECT, BCT, and material efficiency. The main gaps include limited validation, simplified moisture-dependent and failure descriptions, weak interface-damage modeling, and the early development of digital-twin concepts for corrugated board design.

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Keywords: Corrugated board; Structural optimization; Homogenization; Hygro-mechanical behavior; Finite element modeling; Sustainable materials

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CONTENTS

INTRODUCTION

Corrugated board is a widely used lignocellulosic material whose importance has traditionally been associated with packaging and logistics applications (Biancolini and Brutti 2003; Popil and Hojjatie 2010). Its success in these areas is primarily attributed to a unique combination of low density, relatively high stiffness-to-weight ratio, cost-effectiveness, and excellent recyclability (Jannes *et al*. 2023; Kim *et al.* 2023). As a multi-layered composite consisting of paper liners and a corrugated core, it represents a structurally efficient system that can be tailored through geometry, material selection, and layer configuration (Aboura *et al*. 2004; Biancolini 2005a). In the context of increasing environmental awareness and the growing demand for sustainable materials and bio-based alternatives derived from agricultural residues, corrugated board has attracted renewed interest as a potential candidate for broader engineering applications (Jannes *et al.* 2023; Kim *et al.* 2023).

In recent years, the scope of corrugated board usage has gradually extended beyond conventional packaging toward load-bearing and semi-structural applications (Smardzewski and Jasińska 2017; Suarez *et al*. 2021). These include furniture systems, interior design components, protective structures, and temporary architectural solutions (Suarez *et al*. 2021). Such applications require a more advanced understanding of the material behavior under complex loading and environmental conditions (Cornaggia *et al*. 2023; Cornaggia *et al*. 2024), as well as more reliable design methodologies (Fitas *et al*. 2025; Aduke *et al*. 2024). In contrast to traditional packaging design, which is often based on empirical rules and standardized testing, structural applications demand predictive models capable of capturing the mechanical response of the material with sufficient accuracy (Fitas *et al*. 2025; Aduke *et al*. 2024).

The mechanical behavior of corrugated board is inherently complex due to its anisotropic and hierarchical nature (Aboura *et al*. 2004). At the material level, paper exhibits orthotropic properties resulting from the manufacturing process, with distinct differences between the machine direction and cross direction. At the structural level, the interaction between flat liners and the corrugated medium introduces additional geometric nonlinearity and instability mechanisms, such as local buckling, crushing, and shear deformation (Isaksson and Gradin 2009; Viguié and Dumont 2013; Gajewski *et al*. 2021). Furthermore, the effective properties of the composite structure depend not only on the properties of individual layers but also on geometric parameters such as flute shape, wavelength, and height, as well as the so-called take-up factor (Garbowski and Marek 2014). This multiscale character makes direct modeling challenging and motivates the use of homogenization techniques and reduced-order models (Talbi *et al*. 2009; Aduke *et al*. 2023; Mrówczyński *et al*. 2022a,b).

An additional layer of complexity arises from the strong sensitivity of paper-based materials to environmental conditions, particularly moisture and temperature (Cornaggia *et al*. 2023). Hygro-mechanical coupling significantly affects stiffness, strength, and long-term performance, often leading to degradation of mechanical properties and changes in failure mechanisms (Tworzydło *et al*. 2026). In practical applications, this sensitivity introduces uncertainty into the design process, as environmental conditions during service may differ substantially from those assumed in laboratory testing. Despite its importance, the influence of moisture is still insufficiently integrated into most modeling and optimization frameworks for corrugated structures.

To address these challenges, various modeling approaches have been developed over the past decades. Analytical models provide simplified relationships between basic material parameters and global structural performance, often serving as a foundation for engineering design. More advanced approaches include finite element modeling (Heposalmi *et al*. 2022; Fitas *et al*. 2025; Aduke *et al*. 2024), which enables detailed analysis of stress and deformation fields, and homogenization techniques (Talbi *et al*. 2009; Biancolini 2005a; Aduke *et al*. 2023; Garbowski and Jarmuszczak 2014a,b), which aim to derive effective stiffness parameters for use in shell or plate models (Mrówczyński *et al*. 2022a,b; Garbowski *et al*. 2025c). These methods differ in terms of computational cost, required input data, and level of physical fidelity, and their suitability depends on the intended application.

Parallel to the development of modeling techniques, optimization methods have become an increasingly important tool in corrugated board-related engineering design, including production planning, scheduling, waste minimization, and structural design (Bolat 2000; Rodriguez and Vecchietti 2013; Fitas *et al*. 2023). Classical approaches based on gradient methods allow efficient identification of locally optimal solutions, while heuristic and metaheuristic algorithms (Minakawa *et al*. 2025), such as genetic algorithms or particle swarm optimization, offer greater flexibility in exploring complex design spaces. More recently, surrogate-based methods (Chaveesuk *et al*. 2021; Fitas 2025), including those based on reduced-order modeling and machine learning, have gained attention due to their ability to significantly reduce computational cost while maintaining acceptable accuracy. However, the application of these techniques to corrugated board structures remains fragmented, and a comprehensive synthesis of existing approaches is still lacking.

The need for optimization-based design is particularly evident (Fitas *et al*. 2023; Kim *et al*. 2023) in the case of corrugated board, where multiple, often competing objectives must be considered simultaneously. These include mechanical performance (*e.g.*, stiffness, strength, stability), material efficiency, cost, and environmental impact. Moreover, the presence of uncertainties related to material variability and environmental conditions further complicates the design process and calls for robust optimization strategies.

The review by Fitas *et al.* (2023) represents an important reference point for the field, as it systematized optimization practices in the corrugated board industry from a broad industrial and methodological perspective. Their work covered the historical development of optimization, manufacturing and distribution applications, design optimization categories, optimization objectives, and numerical algorithms used in corrugated board-related problems. However, the present review addresses a different level of the problem. Rather than reviewing optimization practices as a general industrial activity, it focuses on the structural-mechanics basis required for reliable optimization of corrugated board as a load-bearing, layered, anisotropic, and environmentally sensitive material.

The aim of this paper is to provide a comprehensive review of optimization techniques in the structural design of corrugated board, with a particular focus on the interplay between material behavior, modeling approaches, and optimization strategies. The paper first discusses key design variables and performance indicators relevant to corrugated structures, followed by an overview of modeling frameworks, including analytical, numerical, and homogenization-based approaches. Subsequently, various optimization techniques are examined and compared in terms of their applicability, advantages, and limitations. Special attention is devoted to the role of hygro-mechanical effects, which are essential for a realistic assessment of paper-based materials but are still underrepresented in existing optimization studies.

Finally, the paper identifies current research gaps and outlines future perspectives, including the integration of environmental effects into design optimization, the development of digital twin concepts, and the use of data-driven methods for performance prediction and inverse design. By bridging the gap between material science, structural mechanics, and optimization, this review aims to support the development of more efficient, reliable, and sustainable corrugated board structures.

Position of the Present Review with Respect to Fitas *et al.* (2023)

The present paper intentionally complements, rather than duplicates, the review by Fitas *et al.* (2023). The distinction between the two works can be summarized in four points. First, Fitas *et al.* (2023) reviewed optimization in the corrugated board industry mainly through the classification of optimization-related publications, including historical developments, manufacturing and distribution problems, design categories, objectives, and numerical algorithms. In contrast, the present review is centered on the mechanical and structural modeling layer that determines whether an optimized design is physically reliable. Therefore, analytical models, detailed finite element models, homogenization procedures, reduced-order models, and surrogate models are compared here primarily in terms of their suitability for structural optimization loops.

Second, the search strategy adopted by Fitas *et al.* (2023) was deliberately focused on papers explicitly using optimization-related terms in the title, which was appropriate for identifying optimization studies as such. The present review adopts a broader mechanics-oriented selection strategy. It also includes papers that may not be labeled as “optimization” papers but provide essential ingredients for optimization-based structural design, such as material characterization, ECT and BCT prediction, bending and shear stiffness identification, local buckling, crushing, homogenization, hygro-mechanical degradation, experimental validation, and surrogate prediction. This broader inclusion is necessary because many optimization-ready models in corrugated board mechanics originate from modeling and testing studies rather than from papers formally framed as optimization studies.

Third, Fitas *et al.* (2023) treated manufacturing, distribution, design, and algorithmic aspects within one broad optimization landscape. The present review narrows the focus to structural design and therefore gives greater attention to model fidelity, validation hierarchy, moisture-dependent properties, interface failure, local instability, and the computational trade-off between detailed FEM and simplified models. These aspects are essential when corrugated board is considered not only as packaging material but also as a lightweight structural medium for panels, furniture, protective components, and temporary structures.

Fourth, the present review explicitly distinguishes mature tools from emerging concepts. Empirical formulas, standardized tests, FEM, and homogenization-based shell or plate models are discussed as established or near-established approaches. Surrogate models and machine-learning tools are treated as promising but validation-sensitive accelerators. Digital twins are presented as a long-term research direction rather than as a mature industrial solution. This maturity-based classification is intended to avoid overstating the readiness of data-driven and real-time design workflows in corrugated board applications.

Accordingly, the added value of this review lies in connecting optimization with the mechanics of corrugated board: model selection, experimental verification, environmental robustness, failure representation, and industrial usability. In this sense, the paper shifts the discussion from "which optimization methods have been used?" toward "which modeling and validation frameworks make structural optimization reliable?"

Table 1. Scope of the Present Review in Comparison with Fitas *et al.* (2023)

Aspect	Fitas *et al.* (2023)	Present review
Main focus	Optimization practices in the corrugated board industry	Structural-mechanics foundations for reliable optimization
Literature selection	Papers explicitly related to optimization, mainly using optimization-related title keywords	Broader mechanics-oriented selection including modeling, testing, homogenization, validation, hygro-mechanics, failure mechanisms, and surrogate prediction
Scope of applications	Manufacturing, distribution, design optimization, objectives, and algorithms	Structural design of corrugated board as a layered anisotropic material and lightweight structural medium
Modeling emphasis	Optimization methods and categories of design variables	Comparison of analytical models, FEM, homogenization, ROM, and surrogate models for optimization loops
Environmental effects	Discussed within the broader optimization landscape	Treated as a central uncertainty source affecting stiffness, strength, validation, and robust design
Failure mechanisms	Not the central axis of the review	Local buckling, crushing, shear instability, delamination, and adhesive-interface degradation
Data-driven methods	Discussed as part of optimization development	Classified by maturity, validation needs, and risk of extrapolation outside the training domain
Digital twins	Not central	Treated cautiously as a long-term research perspective requiring sensing, model updating, and validation

Review Methodology

The literature search was conducted using Scopus, Web of Science, ScienceDirect, SpringerLink, MDPI, Taylor & Francis, and Google Scholar as a complementary source. The search covered primarily publications from 2000 to 2026, while earlier fundamental studies were retained when they introduced widely used empirical formulas, testing concepts, or modeling assumptions. The main search terms included combinations of: "corrugated board", "corrugated cardboard", "paperboard", "structural optimization", "finite element model", "homogenization", "analytical model", "surrogate model", "machine learning", "digital twin", "hygro-mechanical behavior", "moisture", "ECT", "BCT", "SCT", "bending stiffness", "box compression", "buckling", "crushing", and "delamination".

In contrast to the title-based optimization search used by Fitas *et al.* (2023), the present search was not limited to papers explicitly containing "optimization", "optimum", or "optimal" in the title. This decision was made because many studies that are essential for structural optimization of corrugated board are formally published as modeling, testing, homogenization, validation, or material-characterization papers. Although such works may not solve an optimization problem directly, they define the predictive models, constraints, objective functions, and validation procedures on which reliable optimization depends.

Papers were included when they addressed at least one of the following aspects: mechanical characterization, structural modeling, optimization, experimental validation, moisture sensitivity, failure mechanisms, interface behavior, or data-driven prediction of corrugated board and closely related paper-based sandwich structures. Papers dealing only with production scheduling, logistics, or general manufacturing optimization were retained only when they provided methodological context directly relevant to structural optimization. The selected studies were classified into thematic groups corresponding to design variables, performance indicators, modeling frameworks, optimization methods, hygro-mechanical effects, validation strategies, failure mechanisms, and future data-driven developments.

DESIGN VARIABLES AND PERFORMANCE METRICS

The structural design of corrugated board systems involves a complex interplay between material properties, geometric parameters, and environmental conditions (Cornaggia *et al*. 2023). Unlike homogeneous engineering materials, corrugated board exhibits a multi-layered and hierarchical structure (Aboura *et al*. 2004; Biancolini 2005a), where both the characteristics of individual paper layers and the geometry of the corrugated core govern the overall mechanical response. Consequently, the identification of relevant design variables and performance metrics constitutes a fundamental step in the development of optimization-based design frameworks (Aduke *et al*. 2023).

Layered Structure and Fluting Shapes

Design variables in corrugated board structures can be broadly classified into three groups: material-related parameters, geometric characteristics, and structural configuration variables.

At the material level, the mechanical behavior of paper liners and the corrugated medium is primarily defined by orthotropic elastic properties (Beck and Fischerauer 2022), which differ significantly between the machine direction (MD) and cross direction (CD). Key parameters include tensile stiffness and strength in both principal directions, as well as shear stiffness (Huang *et al*. 2012; Garbowski and Gajewski 2021). These properties are typically derived from standardized tests such as the Short-Span Compression Test (SCT) and tensile tests (ISO 9895; ISO 1924-2), and they form the basis for estimating higher-level structural performance indicators.

Geometric variables are of particular importance, as they directly influence the load-carrying capacity and stiffness of corrugated structures (Yuan *et al.* 2014a,b; Garbowski and Borecki 2025). The shape of the flute, commonly approximated as sinusoidal but increasingly explored in alternative forms (Yuan *et al*. 2014a), determines the distribution of stresses and the susceptibility to local buckling. Additional geometric parameters include the flute height, wavelength, and thickness of the medium (Yuan *et al*. 2014a,b), as well as the take-up factor (Garbowski and Marek 2014), which reflects the ratio of the actual length of the corrugated layer to its projected length. The thickness and mechanical properties of the liners also play a crucial role in defining bending stiffness and overall stability (Isaksson and Gradin 2009; Viguié and Dumont 2013).

Structural configuration variables describe the arrangement and number of layers within the system (Mrówczyński *et al*. 2022a,b). These include single-wall, double-wall, and triple-wall configurations (Gajewski *et al*. 2021; Mrówczyński *et al.* 2022b), each offering different levels of stiffness and strength. The orientation of the fluting relative to the loading direction is another critical factor (Popil and Hojjatie 2010), particularly in applications involving bending or shear. Furthermore, design features such as perforations, creases, and cutouts (Johnson *et al*. 2019; Garbowski *et al*. 2021c), commonly introduced for functional or manufacturing purposes, can significantly affect the structural integrity and must be considered in the design process.

In addition to the above, environmental variables, particularly moisture content and temperature, should be regarded as implicit design parameters. Although they are not controlled in the same way as geometric or material variables, their influence on mechanical performance is substantial and often comparable to that of primary design parameters. Therefore, their inclusion in advanced design and optimization frameworks is essential (Cornaggia *et al*. 2023; Tworzydło *et al*. 2026).

Performance Metrics

The performance of corrugated board structures is evaluated using a combination of standardized test results and derived mechanical indicators (ISO 3037; ISO 9895; ISO 12048). These metrics serve both as objective functions and constraints in optimization problems.

Among the most widely used indicators is the Edge Crush Test (ECT) (Garbowski *et al*. 2021a; ISO 3037), which provides a measure of the compressive strength of corrugated board in the edgewise direction. ECT is closely related to the load-bearing capacity of boxes and is often used as a primary design parameter in packaging applications. Since ECT performance depends strongly on the compressive response of the constituent papers, predictive models of the corrugated medium itself remain highly relevant for strength-oriented design (Desloges-Vullierme *et al*. 2008).

From the experimental point of view, the verification of corrugated board models should be linked to standardized or well-defined test procedures. ECT and SCT are commonly used to characterize edgewise and short-span compressive response, tensile tests provide paper-level orthotropic input data, while BCT evaluates the global load-bearing capacity of boxes. Four-point bending tests are particularly relevant for validating bending stiffness, whereas shear-related tests and torsion-based procedures are needed when homogenized transverse shear stiffness is used in plate or shell models. For models intended for service conditions, these tests should ideally be combined with controlled humidity conditioning and, where relevant, creep or long-term loading protocols (ISO 3037; ISO 9895; ISO 12048; ISO 1924-2; ISO 187; ASTM D642; ASTM D4577; ASTM D7030).

Similarly, the Box Compression Test (BCT) (Biancolini and Brutti 2003; Popil and Hojjatie 2010; ISO 12048; ASTM D642) evaluates the global load capacity of a box and is frequently correlated with ECT through empirical relationships. Box compression strength is one of the most important indicators of packaging performance; however, long-term creep under sustained stacking loads may be equally critical for service-life reliability (Holmvall 2022; ASTM D4577; ASTM D7030).

Bending stiffness is another key performance metric (Viguié and Dumont 2013; Garbowski and Gajewski 2021), particularly in applications involving panels or structural elements subjected to flexural loading. It is commonly determined through four-point bending tests (ISO 5628) and depends strongly on both the stiffness of individual layers and the geometry of the corrugated core. Shear stiffness, although less frequently measured directly (Isaksson and Gradin 2009), plays a crucial role in the overall deformation behavior, especially in thick or multi-layered configurations where transverse shear effects become significant.

Stability-related parameters, including resistance to local and global buckling (Isaksson and Gradin 2009; Mrówczyński and Garbowski 2023), are also important, particularly in load-bearing applications. These phenomena are influenced by geometric imperfections, material nonlinearity, and boundary conditions, making them more challenging to quantify using simple test methods.

In addition to mechanical performance, practical design often requires consideration of material efficiency, typically expressed in terms of mass or material usage, as well as cost-related indicators (Jannes *et al*. 2023; Kim *et al*. 2023). Increasingly, environmental metrics, such as recyclability, and carbon footprint, are also being incorporated into design objectives, reflecting the growing importance of sustainable engineering practices.

Relationship Between Variables and Performance

The relationship between design variables and performance metrics is highly nonlinear and often involves strong coupling effects (Yuan *et al*. 2014a,b; Mrówczyński *et al.* 2022c). For example, an increase in flute height may improve bending stiffness but at the same time reduce resistance to local buckling (Isaksson and Gradin 2009; Yuan *et al*. 2014a). Similarly, increasing liner thickness enhances compressive strength but leads to higher material consumption and cost (Popil and Hojjatie 2010; Kim *et al*. 2023).

Table 2. Key Design Variables and their Influence on the Structural Performance of Corrugated Board

Category	Variable	Description	Primary Influence	Typical Evaluation
Material	MD/CD stiffness	Orthotropic elastic properties of paper	Bending, ECT, global stiffness	Tensile test, SCT
Material	Shear stiffness	In-plane shear behavior of paper	Shear deformation, stability	Shear tests, indirect
Geometry	Flute shape	Sinusoidal or alternative geometry	Stress distribution, buckling	Analytical/FEM
Geometry	Flute height	Distance between liners	Bending stiffness, stability	Bending tests
Geometry	Wavelength	Flute period	Stiffness, load distribution	Analytical/ FEM
Geometry	Take-up factor	Length ratio of corrugated layer	Material usage, stiffness	Analytical
Structure	Layer configuration	Single/double/triple wall	Strength, stiffness	ECT, BCT
Structure	Orientation (MD/CD)	Loading direction vs. fluting	Anisotropy effects	Experimental
Structure	Perforations/ creases	Functional modifications	Local weakening, failure	Experimental
Environment	Moisture content	Relative humidity influence	Stiffness, strength degradation	Climate chamber tests
Environment	Temperature	Thermal effects	Coupled with moisture	Controlled tests

This multi-objective and interdependent nature of the design space highlights the necessity of systematic optimization approaches (Fitas *et al*. 2023; Mrówczyński *et al*. 2022c) capable of balancing competing requirements. It also underscores the importance of selecting an appropriate set of design variables and performance metrics, as their definition directly influences the outcome and relevance of the optimization process.

To facilitate a structured analysis, Table 2 summarizes the key design variables, their physical meaning, and their primary influence on selected performance metrics.

MODELING FRAMEWORKS FOR STRUCTURAL DESIGN OF CORRUGATED BOARD

Accurate modeling of corrugated board is a prerequisite for any optimization-based design approach, and recent review studies have summarized the main numerical homogenization routes available for such applications. Due to its heterogeneous, layered structure and strong anisotropy, the material cannot be described adequately using simple homogeneity assumptions (Aboura *et al*. 2004). Instead, a range of modeling strategies has been developed, differing in terms of complexity, computational cost, and level of physical fidelity (Talbi *et al*. 2009; Aduke *et al*. 2023; Garbowski 2025; Fitas *et al*. 2025). These approaches can be broadly categorized into analytical models, homogenization techniques, and detailed numerical simulations.

Analytical Models

Analytical models represent the earliest and most widely used approach for predicting the mechanical performance of corrugated board (Biancolini and Brutti 2003). These models typically rely on simplified mechanical assumptions and empirical relationships derived from experimental observations (Biancolini and Brutti 2003; ISO 3037). Classical examples include formulations linking the Edge Crush Test (ECT) (Garbowski *et al*. 2021a; Garbowski and Andrzejak 2022) to the compressive strength of individual paper layers, as well as semi-empirical equations for estimating the Box Compression Test (BCT) (Biancolini and Brutti 2003; Johnson *et al*. 2019) based on geometric parameters and material properties.

The main advantage of analytical models lies in their simplicity and computational efficiency, which makes them attractive for preliminary design and industrial applications. However, their applicability is limited (Viguié and Dumont 2013; Mrówczyński and Garbowski 2023) by the underlying assumptions, which often neglect local effects such as geometric imperfections, nonlinear material behavior, and complex failure mechanisms. As a result, analytical models are generally insufficient for capturing the full structural response of corrugated systems, particularly in non-standard configurations or advanced applications.

Homogenization Approaches

To overcome the limitations of purely analytical formulations, homogenization techniques have been developed (Biancolini 2005a; Talbi *et al*. 2009; Aduke *et al*. 2023; Garbowski and Jarmuszczak 2014a,b) to derive equivalent mechanical properties of corrugated board at the macroscopic level. In this approach, the complex geometry of the corrugated core and liners is replaced by an equivalent continuous medium (Biancolini 2005a) characterized by effective stiffness parameters.

Homogenization is typically performed on a representative volume element (RVE) (Garbowski and Marek 2014) of the corrugated structure, taking into account the geometry of the flute and the orthotropic properties of the paper layers. The resulting effective properties are often expressed in terms of stiffness matrices, such as the classical ABD matrix (Garbowski *et al*. 2025c; Aduke *et al.* 2023) used in laminated plate theory, as well as transverse shear stiffness terms (Garbowski and Gajewski 2021). These parameters can then be used in shell or plate models (Mrówczyński *et al*. 2022a,b) to simulate the behavior of larger structures with significantly reduced computational cost.

An important aspect of homogenization is the treatment of shear deformation (Isaksson and Gradin 2009), which plays a crucial role in corrugated structures due to the relatively low shear stiffness of the core. Various approaches have been proposed to define appropriate transverse shear stiffness and shear correction factors, including energy-consistent numerical identification procedures that ensure consistency between detailed and reduced models (Garbowski and Gajewski 2021). More advanced formulations also consider nonlinear effects, such as local buckling (Mrówczyński and Garbowski 2023) of the corrugated medium, and may incorporate voxel-based or layer-wise representations to improve accuracy.

The key advantage of homogenization lies in its ability to balance accuracy and efficiency, making it particularly suitable for optimization problems involving repeated evaluations of structural response. However, the accuracy of the method depends strongly on the assumptions made at the microscale and on the quality of the input data, including material properties and geometric parameters.

Finite Element Modeling

Finite element modeling (FEM) provides a more detailed and flexible framework for corrugated board analysis, particularly when combined with constitutive descriptions adapted to multiwall flute geometries such as double-B configurations (Huang *et al*. 2012; Heposalmi *et al*. 2022; Mrówczyński *et al*. 2022a; Mrówczyński and Garbowski 2023). Analytical homogenization methods have also been developed to efficiently represent corrugated board in finite element simulations without explicitly modeling each flute (Talbi *et al*. 2009). In parallel, equivalent-layer approaches based on multistep homogenization have been developed to determine the effective elastic constants of corrugated board structures (Zhou and Chen 2009).

Depending on the level of detail required, FEM models can be constructed at different scales (Wang 2011a; Beck and Fischerauer 2022), ranging from full three-dimensional representations of the corrugated geometry to simplified two-dimensional shell or plate models based on homogenized properties. Finite element methods have also been employed for direct size optimization of flute-shaped corrugated board structures (Yuan *et al*. 2014a). Additionally, they have been utilized for flute-shape analysis and optimization of corrugated board structures (Yuan *et al*. 2014b).

Detailed 3D models explicitly represent the geometry and local interactions between liners and medium (Zhang *et al.* 2014; Luong *et al.* 2018) of the corrugated core and liners, allowing for accurate prediction of stress distributions, local buckling, and failure mechanisms. Such models are particularly useful for fundamental studies (Viguié and Dumont 2013) and validation of simplified approaches. However, they are computationally expensive and therefore not well suited for large-scale optimization or parametric studies.

In contrast, 2D models based on shell or plate elements offer a more efficient alternative (Talbi *et al*. 2009; Mrówczyński *et al*. 2022a), especially when combined with homogenized stiffness parameters. These models are widely used in engineering practice (Park *et al.* 2012; Aduke *et al*. 2023, 2024) and can capture the global behavior of structures with reasonable accuracy. Nevertheless, their ability to represent local phenomena is limited, and additional modeling assumptions are often required.

A key challenge in FEM modeling of corrugated board is the representation of boundary conditions, contact interactions, and imperfections (Johnson *et al*. 2019; Mrówczyński and Garbowski 2023), all of which can significantly influence the predicted response. Furthermore, the strong dependence of material properties on environmental conditions (Cornaggia *et al*. 2023) adds another layer of complexity, requiring careful calibration and validation against experimental data.

Multi-Scale and Reduced-Order Modeling

Given the computational demands of detailed numerical simulations, there is increasing interest in multiscale and reduced-order modeling techniques. These approaches aim to retain the essential features of the structural response while significantly reducing computational cost.

Multiscale methods combine detailed microscale models with macroscopic representations (Aduke *et al.* 2023; Garbowski *et al*. 2025a), allowing for the transfer of information between scales. In the context of corrugated board, this often involves using RVE-based homogenization to derive effective properties, which are then employed in global structural analyses.

Reduced-order models, including those based on proper orthogonal decomposition (POD) and other dimensionality-reduction techniques, provide an additional level of efficiency for repeated design evaluations. When combined with surrogate modeling approaches, such as response surface methods, Gaussian processes, or neural networks, they enable rapid evaluation of structural performance across a wide range of design configurations (Chaveesuk *et al*. 2021; Fitas 2025).

These methods are particularly well suited for optimization problems (Chaveesuk *et al*. 2021; Fitas 2025), where numerous model evaluations are required. However, their accuracy depends on the quality of the training data and the representativeness of the reduced basis, which must be carefully selected.

Comparison of Modeling Approaches

The choice of a modeling framework strongly affects the feasibility and reliability of optimization. In corrugated board design, the main trade-off is between physical fidelity and computational efficiency. This aspect is particularly important in the present review, because its scope differs from broad optimization surveys by focusing on the mechanics-based reliability of structural optimization. Analytical and semi-empirical models are attractive for preliminary design and industrial screening, but they usually cannot resolve local buckling, crushing, interface damage, or non-standard geometries. Detailed three-dimensional FEM can explicitly represent the fluting geometry, liners, contact conditions, imperfections, and local failure mechanisms, but its computational cost limits its direct use in large optimization loops. Homogenized shell or plate models offer a practical compromise by replacing the detailed corrugated structure with equivalent stiffness parameters. Reduced-order and surrogate models further reduce computation time, but their reliability depends on the representativeness of training data and on validation within the admissible design domain (Biancolini 2005a; Talbi *et al*. 2009; Aduke *et al*. 2023; Fitas *et al*. 2025; Chaveesuk *et al*. 2021).

Table 3. Comparison of Modeling Approaches Used in Corrugated Board Structural Design

Modeling Approach	Typical Input Data	Accuracy and Validation	Computational Cost	Local Buckling / Crushing / Delamination	Suitability for Optimization
Analytical and semi-empirical models	Board geometry, paper strength, ECT/SCT/BCT-type indicators	Good for standard configurations when calibrated; limited outside empirical range	Very low	Usually not resolved explicitly	Very high for preliminary screening and industrial design
Detailed 3D FEM	Full flute geometry, orthotropic paper properties, contact/interface assumptions, boundary conditions	Potentially high, but strongly dependent on calibration and experimental validation	High to very high	Can capture local buckling, crushing and interface failure if appropriate nonlinear and cohesive/contact models are used	Limited for direct optimization; useful for benchmarks and training data
Homogenized shell/plate models	Equivalent ABD and shear stiffnesses from analytical or numerical homogenization	Good for global stiffness and deformation; less reliable for local failure unless enriched	Low to moderate	Local effects are usually represented indirectly or through additional criteria	High for structural optimization of boxes, panels and multiwall boards
Reduced-order models	Snapshots from FEM or experiments, reduced basis, selected design variables	Accurate within the sampled parameter range; requires careful error control	Very low after construction	Only captured if present in training snapshots and reduced representation	High, especially for repeated evaluations
Surrogate and machine-learning models	Experimental or simulation datasets, input design variables, target performance indicators	Depends strongly on dataset size, sampling strategy, validation and extrapolation control	Very low after training	Not physical by default; failure modes must be encoded through data or hybrid physics-based features	Very high, but only within a validated design domain

Direct quantitative comparisons between these approaches remain difficult because published studies often use different board grades, geometries, conditioning procedures, boundary conditions, and validation metrics. The absence of standardized benchmark datasets comparing analytical models, detailed FEM, homogenized models, and surrogate predictions against the same experimental results should therefore be regarded as a significant research gap.

Interface Failure and Delamination Modeling

Most simplified models of corrugated board assume perfect bonding between liners and the corrugated medium. This assumption is often acceptable for predicting the initial elastic stiffness and global deformation, but it becomes insufficient when progressive damage, bending failure, impact, humidity exposure, or long-term loading are considered. In real corrugated board structures, the adhesive interface may degrade, soften, or fail, leading to local delamination and a redistribution of load transfer between the liners and the fluting. Such mechanisms may strongly affect bending stiffness, crushing resistance, buckling behavior, and residual load-bearing capacity (Twede and Selke 2005; Gajewski *et al.* 2021; Cornaggia *et al.* 2023; Ai *et al*. 2025).

From a modeling perspective, interface failure can be represented at different levels of complexity. In detailed FEM, cohesive-zone models or interface elements may be used to describe traction-separation behavior, including damage initiation and evolution governed by interface strength and fracture energy. Contact-based formulations with damage or debonding criteria can also be applied when separation and possible re-contact are important. In homogenized or shell-based models, delamination is more difficult to represent explicitly; therefore, simplified degradation laws, reduced bond-stiffness parameters, or additional failure criteria are often required (Ai *et al*. 2025; Bian and Qing 2021). Moisture-dependent adhesive degradation is especially important, because increased humidity may reduce bond strength and change the dominant failure mode from material crushing to interface-controlled damage. The limited availability of validated interface parameters for corrugated board remains an important obstacle to predictive failure modeling and should be treated as a priority in future experimental and numerical studies (Twede and Selke 2005; Ai *et al*. 2025; Bian and Qing 2021).

OPTIMIZATION TECHNIQUES IN THE STRUCTURAL DESIGN OF CORRUGATED BOARD

Optimization techniques play a central role in enabling performance-driven design of corrugated board structures (Bolat 2000; Rodriguez and Vecchietti 2013; Fitas *et al*. 2023). In industrial practice, optimization also extends beyond structural parameters to production planning, scheduling, and waste minimization in corrugated box plants (Bolat 2000; Glasenapp *et al*. 2010; Mansour *et al*. 2024). Given the large number of interacting design variables and the presence of multiple, often conflicting objectives, traditional trial-and-error approaches are insufficient for achieving efficient and robust solutions. Instead, systematic optimization methods provide a framework for exploring the design space and identifying configurations that satisfy structural, economic, and environmental requirements (Fitas *et al*. 2023; Jannes *et al*. 2023). In the context of the present review, however, optimization techniques are not discussed as isolated algorithms. They are considered together with the predictive models, experimental data, and failure criteria that define the objective functions and constraints of a physically meaningful structural design problem.

In the context of corrugated board, optimization problems typically involve the selection of geometric parameters, material properties, and structural configurations to maximize or minimize specific performance indicators, such as strength, stiffness, or material usage (Yuan *et al*. 2014a; Mrówczyński *et al*. 2022b). These problems are often constrained by practical considerations, including manufacturability, standardization, and sensitivity to environmental conditions.

Formulation of Optimization Problems

The formulation of an optimization problem requires the definition of design variables, objective functions, and constraints. Design variables include flute geometry, layer configuration, and material properties, while performance metrics such as ECT, bending stiffness, and buckling resistance serve as objective functions or constraints (Garbowski and Gajewski 2021; Garbowski and Andrzejak 2022; Yuan *et al*. 2014a,b; Mrówczyński *et al*. 2022b).

In a generic form, a single-objective corrugated board optimization problem can be written as

$$\min_{x \in \Omega} f(\mathbf{x}) \tag{1}$$

subject to

$$g_i(\mathbf{x}) \leq 0, \quad i = 1, \ldots, n_g \tag{2}$$

$$h_j(\mathbf{x}) = 0, \ j = 1, \ldots, n_h \tag{3}$$

Here, $\mathbf{x}$ denotes the vector of design variables, which may include flute height, wavelength, take-up factor, liner and medium thicknesses, paper grades, layer configuration, board orientation, or selected manufacturing parameters. The objective function $f(\mathbf{x})$ may represent material consumption, mass, cost, carbon footprint, or the negative of a mechanical performance indicator when maximization is required. The inequality constraints $g_i(\mathbf{x})$ may impose minimum ECT, BCT, bending stiffness, buckling resistance, allowable deflection, stress limits, or interface-failure limits, while equality constraints $h_j(\mathbf{x})$ may represent prescribed dimensions or manufacturing requirements.

For multi-objective design, the problem may be expressed as,

$$\min_{\mathbf{x} \in \Omega} \mathbf{F}(\mathbf{x}) = [f_1(\mathbf{x}), f_2(\mathbf{x}), \ldots, f_m(\mathbf{x})]^T \tag{4}$$

where the objectives may simultaneously include mechanical performance, mass, cost, and environmental indicators. In such cases, the solution is not a single optimum but a set of Pareto-optimal designs representing different compromises between competing requirements.

When environmental or material uncertainty is included, the deterministic vector $\mathbf{x}$ is accompanied by uncertain parameters $\boldsymbol{\xi}$, such as paper-property variability, moisture content, relative humidity, temperature, or manufacturing tolerances. A robust formulation may then be written as,

$$\min_{\mathbf{x} \in \Omega} \left[E\big(f(\mathbf{x}, \boldsymbol{\xi})\big) + \lambda\, Std\big(f(\mathbf{x}, \boldsymbol{\xi})\big) \right] \tag{5}$$

which is subject to probabilistic or worst-case constraints on strength, stiffness, stability, or serviceability. This formulation is particularly relevant for corrugated board because designs optimized only under nominal laboratory conditions may not remain safe or efficient under variable humidity or long-term storage conditions. In many cases, the optimization problem is inherently multi-objective (Misawa and Kanezashi 2005; Minakawa *et al*. 2025). For example, increasing stiffness or strength often leads to higher material consumption and cost, while reducing weight may compromise structural integrity (Jannes *et al*. 2023; Kim *et al*. 2023). Therefore, trade-offs must be carefully balanced, either by combining objectives into a single scalar function or by adopting multi-objective optimization strategies that generate Pareto-optimal solutions (Minakawa *et al*. 2025).

An additional challenge arises from the presence of uncertainties, particularly those related to material variability and environmental effects. Incorporating these uncertainties into the optimization framework leads to robust or reliability-based optimization formulations, which aim to ensure satisfactory performance under a range of possible conditions. Sensitivity-oriented formulations have also been explored using non-local sensitivity measures for corrugated board packaging design (Mrówczyński *et al*. 2022c).

Gradient-Based Methods

Gradient-based optimization methods are among the most widely used techniques in engineering design. These methods rely on the evaluation of sensitivities, *i.e.*, derivatives of the objective function with respect to design variables, to guide the search for optimal solutions.

The main advantage of gradient-based methods is their computational efficiency, especially when combined with analytical or semi-analytical models (Yuan *et al*. 2014b). They are particularly effective for problems with a relatively small number of design variables and smooth response surfaces. In the context of corrugated board, they can be applied to optimize parameters such as flute geometry or layer thickness when the underlying model is sufficiently well-behaved (Yuan *et al*. 2014b).

However, gradient-based methods are inherently local, meaning that they may converge to suboptimal solutions if the design space contains multiple local minima. Moreover, the computation of accurate gradients can be challenging when using complex numerical models, especially in the presence of nonlinearity or discontinuities associated with failure mechanisms.

Heuristic and Metaheuristic Algorithms

To overcome the limitations of gradient-based approaches, heuristic and metaheuristic algorithms have been increasingly adopted in structural optimization. These methods, including genetic algorithms (GA), particle swarm optimization (PSO), and simulated annealing, are designed to explore the design space more globally without relying on gradient information (Fitas *et al*. 2023; Misawa and Kanezashi 2005; Minakawa *et al.* 2025). In corrugated board applications, such methods are most relevant when the design variables include discrete flute types, layer configurations, box dimensions, or manufacturing constraints that cannot be easily handled by gradient-based algorithms.

Such algorithms are particularly useful for problems involving discrete variables, complex constraints, or highly nonlinear behavior (Misawa and Kanezashi 2005; Minakawa *et al*. 2025). In the case of corrugated board, they have been applied to optimize packaging configurations, structural layouts, and material distributions.

The main drawback of heuristic methods is their relatively high computational cost, as they typically require numerous function evaluations. This limitation becomes particularly significant when each evaluation involves a detailed finite element analysis. As a result, their practical application often necessitates the use of simplified models or surrogate-based approaches.

Surrogate-Based Optimization

Surrogate-based optimization has emerged as a powerful strategy for reducing the computational burden associated with complex modeling frameworks. In this approach, a simplified model, or surrogate, is constructed to approximate the relationship between design variables and performance metrics.

Common surrogate modeling techniques include response surface methods, Gaussian process regression, and artificial neural networks (Chaveesuk *et al*. 2021; Fitas 2025). Recent studies have demonstrated that Gaussian process surrogates can be combined with expected hypervolume improvement criteria to efficiently solve multi-objective corrugated board design problems involving stiffness and geometric parameters (Fitas 2025). More advanced approaches may incorporate reduced-order modeling techniques, such as proper orthogonal decomposition (POD), to capture the dominant features of the system behavior.

In the context of corrugated board, surrogate models are particularly attractive due to the multiscale nature of the problem and the high cost of detailed numerical simulations. By replacing expensive models with fast approximations, surrogate-based methods enable efficient exploration of the design space and facilitate the application of both gradient-based and heuristic optimization algorithms.

However, the accuracy and reliability of surrogate models depend on the quality and representativeness of the training data. Careful selection of sampling strategies and validation procedures is therefore essential to ensure that the surrogate model provides meaningful predictions across the relevant range of design variables (Chaveesuk *et al*. 2021; Fitas 2025).

For this reason, surrogate and machine-learning studies should be reported together with clear validation information. At minimum, the description should include the size and origin of the dataset, the input variables, the predicted output quantities, the sampling strategy, and the validation procedure. Depending on the study, relevant error measures may include RMSE, MAE, MAPE, the coefficient of determination (R^2), prediction intervals, or errors in selected performance indicators such as ECT, BCT, bending stiffness, or critical load. It is also important to distinguish between models validated against independent experimental data and models validated only against numerical simulations. The latter may be useful for accelerating high-fidelity computational models but cannot by themselves confirm predictive accuracy with respect to real corrugated board behavior.

In the context of corrugated board optimization, surrogate models should therefore be treated as fast approximations within a clearly defined design domain rather than as universal predictors. Extrapolation beyond the range of paper grades, flute geometries, humidity conditions, or board configurations used in training may lead to unreliable predictions. This limitation is particularly important when surrogate models are used inside optimization algorithms, because the optimizer may otherwise identify apparently optimal but physically unsupported designs (Chaveesuk *et al*. 2021; Fitas 2025).

Multi-Objective Optimization

Many design problems involving corrugated board structures require the simultaneous consideration of multiple objectives, such as maximizing strength while minimizing material usage or environmental impact (Jannes *et al*. 2023; Kim *et al*. 2023; Minakawa *et al*. 2025). Multi-objective optimization techniques address this challenge by identifying a set of Pareto-optimal solutions, each representing a different trade-off between competing objectives.

These solutions can be visualized as a Pareto front, which provides valuable insight into the structure of the design space and supports informed decision-making. In practical applications, the selection of a final design often involves additional criteria or preferences, which may be introduced through weighting schemes or decision-making frameworks.

Multi-objective optimization is particularly relevant for sustainable design, where environmental considerations must be balanced against mechanical performance and cost. In the case of corrugated board, this may involve optimizing the geometry and material composition to reduce resource consumption while maintaining adequate structural performance.

Integration with Modeling Frameworks

The effectiveness of any optimization technique is closely linked to the underlying modeling framework and to the level at which the corrugated geometry is represented. Analytical models enable rapid evaluations but may lack accuracy, while detailed numerical models provide high fidelity at a significant computational cost. Homogenization and reduced-order models offer a compromise, making them particularly suitable for optimization tasks.

The integration of optimization methods with appropriate modeling approaches is a critical aspect of the design process. Surrogate-based optimization can be combined with high-fidelity models to achieve both accuracy and efficiency, while gradient-based methods may benefit from reduced-order representations that facilitate sensitivity analysis (Biancolini 2005a; Talbi *et al*. 2009; Aduke *et al*. 2023; Fitas *et al*. 2025).

Emerging Trends and Challenges

Despite significant progress, the application of optimization techniques to corrugated board structures remains limited in several respects. A main challenges is the incorporation of hygro-mechanical effects into optimization frameworks, as environmental conditions introduce additional variables and uncertainties that are difficult to model accurately (Cornaggia *et al*. 2023; Tworzydło *et al*. 2026). Another emerging trend is the integration of data-driven methods, including machine learning, into prediction and optimization workflows (Chaveesuk *et al*. 2021; Fitas 2025). Up to now, such approaches have mainly been demonstrated as surrogate predictors, quality-control tools, or accelerators of numerical simulations. Their practical value depends on the availability of representative datasets, transparent validation, and a clearly defined range of applicability. Therefore, machine-learning models should be distinguished from established mechanics-based models: they can efficiently approximate complex relationships between design variables and performance metrics, but they do not automatically provide physical reliability outside the training domain. Digital-twin concepts should be treated with even greater caution in the context of corrugated board structural design. While digital twins are conceptually attractive because they combine sensing, model updating, prediction, and decision support, fully operational implementations for corrugated board structures remain limited. At present, their application should be regarded mainly as a long-term research direction rather than a mature industrial design tool. Their development requires reliable sensors, online data acquisition, validated reduced-order or surrogate models, uncertainty quantification, and procedures for updating model parameters during production, storage, transport, or service (Biancolini 2005b; Garbowski and Karasiewicz 2026). The interaction between modeling fidelity, optimization strategy, validation, and potential digital-twin feedback is summarized in Fig. 1.

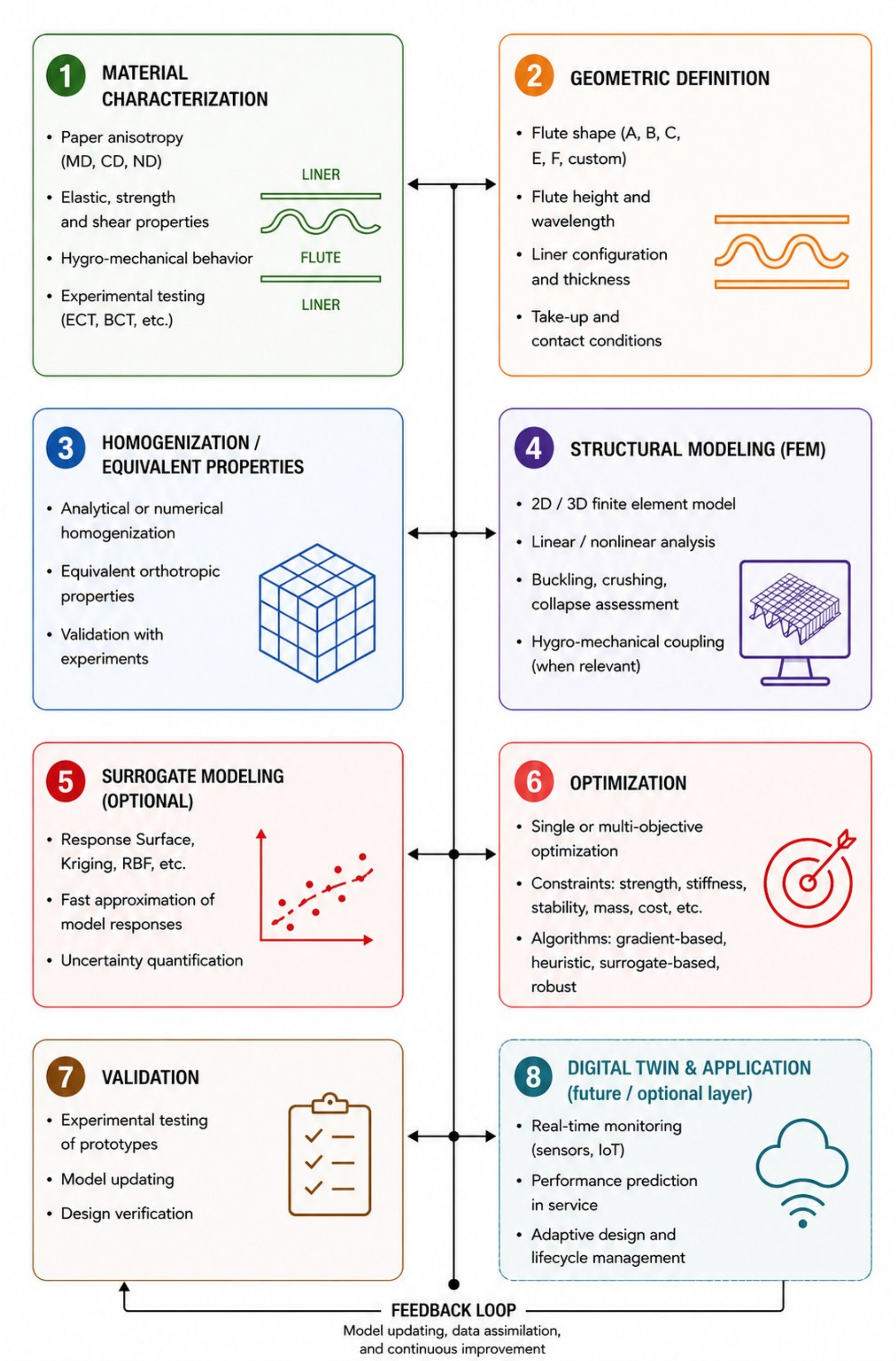

Fig. 1. Integrated design and optimization workflow for corrugated board structures, linking material characterization, geometric definition, homogenization, structural modeling, surrogate learning, optimization, experimental validation, and potential digital-twin feedback

APPLICATIONS OF OPTIMIZATION IN CORRUGATED BOARD STRUCTURES

The application of optimization techniques to corrugated board structures has evolved alongside advances in modeling, homogenization, and computational design methods (Talbi *et al*. 2009). While early efforts were primarily focused on packaging design, recent developments have extended the scope of optimization to a broader range of engineering applications. These include structural panels, furniture systems, and emerging building components, where the material is increasingly considered as a viable alternative to traditional solutions (Smardzewski and Jasińska 2017; Suarez *et al*. 2021).

Packaging Structures

Packaging remains the most mature and extensively studied application area for corrugated board (Biancolini and Brutti 2003; Popil and Hojjatie 2010), with recent studies addressing the optimal design of advanced double-wall corrugated packaging systems (Mrówczyński *et al*. 2022b). Beyond material strength itself, the global stability of corrugated board packages remains a practical determinant of safe stacking and logistics performance (Garbowski and Borysiewicz 2014). Recent packaging studies also emphasize dynamic transport loads and corner-impact situations, which broaden the optimization problem beyond static compression capacity (Gao and Lu 2013; Cáceres-Naranjo *et al.* 2024).

In this domain, optimization is primarily driven by the need to minimize material usage while ensuring sufficient load-bearing capacity during storage and transport, including package-volume optimization and impact-related performance (Kubera and Tyczyński 2009; Luong *et al*. 2018; Kumbhar *et al*. 2025). Increasing emphasis is also placed on pallet-package interactions and sustainability objectives (Kim *et al*. 2022; Jannes *et al*. 2023; Kim *et al*. 2023). The design of corrugated boxes is typically governed by performance indicators such as ECT and BCT, which are used either directly or through empirical relationships (Yuan *et al*. 2013). However, box compression strength is also influenced by pallet top-deck stiffness and other unit-load design variables (Kim *et al*. 2021, 2022, 2023). Numerical strength estimation of corrugated board packages has also been studied using combined theoretical, experimental, and finite element approaches (Garbowski and Jarmuszczak 2014c,d).

Optimization approaches in packaging often focus on geometric parameters, such as flute type, board thickness, and box dimensions, as well as material selection for liners and medium (Yuan *et al*. 2014a,b). Both analytical and numerical models have been used to support this process, with increasing adoption of optimization algorithms to identify configurations that achieve a desired balance between strength and cost.

In industrial practice, simplified models are frequently employed due to time and cost constraints. However, the growing availability of computational tools has enabled the use of more advanced methods, including surrogate-based optimization, to improve design efficiency. These approaches allow for rapid evaluation of multiple design variants and support the development of lightweight yet reliable packaging solutions (Kim *et al*. 2023).

From the optimization perspective, packaging structures remain the most suitable benchmark application because they combine standardized performance indicators, such as ECT and BCT, with clear industrial constraints related to weight, cost, manufacturability, storage, and transport. However, when the same material is considered for panels, furniture, protective components, or temporary structures, additional verification of bending stiffness, shear stiffness, buckling resistance, interface integrity, and environmental sensitivity becomes necessary (Biancolini and Brutti 2003; Popil and Hojjatie 2010; Fitas *et al*. 2023).

Sandwich and Panel Structures

Corrugated board is structurally analogous to sandwich panels, where the corrugated medium acts as a core separating two stiff liners (Viguié and Dumont 2013; Garg *et al*. 2014; Smardzewski and Jasińska 2017). This analogy has led to the exploration of corrugated board in panel applications, particularly where lightweight and cost-effective solutions are required (Smardzewski and Jasińska 2017). Beyond paperboard, corrugated-core concepts are also optimized in broader engineering applications to reduce stress concentrations and improve structural efficiency (Zhang *et al*. 2023; Sun *et al*. 2024; Wang and Jiang 2024).

Optimization in this context typically involves the adjustment of geometric parameters, such as core height and flute configuration, to maximize bending stiffness and load-carrying capacity while minimizing material usage (Yuan *et al*. 2014a; Garbowski and Gajewski 2021). Homogenization techniques are often employed to derive effective properties for use in plate or shell models, enabling efficient analysis of larger structures (Garbowski and Marek 2014; Aduke *et al*. 2023).

In comparison to packaging applications, panel structures require a more detailed consideration of deformation and stability, including shear effects and local buckling (Isaksson and Gradin 2009; Mrówczyński and Garbowski 2023). As a result, optimization problems in this area tend to be more complex and often rely on numerical methods combined with reduced-order models.

Furniture and Lightweight Structures

The use of corrugated board in furniture and lightweight structural systems represents an intermediate step between packaging and full-scale structural applications (Suarez *et al*. 2021). In these systems, the material is subjected to repeated loading and must satisfy both strength and serviceability requirements, such as limited deflections.

Optimization techniques have been applied to improve the structural efficiency of cardboard furniture by adjusting parameters such as layer configuration, folding patterns, and local reinforcements (Suarez *et al.* 2021). These design variables often involve discrete choices, making heuristic optimization methods potentially useful.

In addition to mechanical performance, aesthetic and functional considerations play an important role in furniture design. This introduces additional complexity into the optimization process, as multiple criteria must be balanced simultaneously. Despite these challenges, the use of optimization has contributed to the development of innovative and resource-efficient designs (Jannes *et al*. 2023).

Building and Architectural Applications

The application of corrugated board in building and architectural contexts is an emerging field with significant potential (Smardzewski and Jasińska 2017). Examples include temporary shelters, exhibition structures, and interior architectural elements, where the material offers advantages in terms of sustainability, ease of fabrication, and low environmental impact (Suarez *et al.* 2021; Jannes *et al*. 2023; Kim *et al*. 2023). Outside conventional packaging and structural applications, corrugated paper structures have also been explored in functional applications such as conductive electromagnetic absorbers, demonstrating the broader engineering potential of corrugated geometries (Imai *et al*. 2010).

In these applications, optimization plays a critical role in ensuring structural safety and performance under more demanding conditions. Design objectives may include maximizing load-bearing capacity, minimizing deflections, and improving resistance to environmental effects such as moisture.

Compared to packaging and furniture, building applications require a more rigorous treatment of structural behavior, including stability, long-term performance, and reliability under variable environmental conditions (Isaksson and Gradin 2009; Mrówczyński and Garbowski 2023). This necessitates the use of advanced modeling techniques and robust optimization frameworks capable of handling uncertainty.

Although still at an early stage of development, optimization-based design in this area has the potential to significantly expand the use of corrugated board in construction (Smardzewski and Jasińska 2017). In particular, the integration of material modeling, structural analysis, and environmental considerations offers a promising direction for future research (Cornaggia *et al*. 2023).

HYGRO-MECHANICAL EFFECTS AND ENVIRONMENTAL SENSITIVITY

The mechanical performance of corrugated board is strongly influenced by environmental conditions, particularly moisture and temperature (Cornaggia *et al*. 2023; Tworzydło *et al*. 2026). As a lignocellulosic material, paper exhibits pronounced hygroscopic behavior, meaning that it readily absorbs and desorbs moisture from the surrounding environment. This behavior is rooted in moisture sorption within the cellulose-fiber network and the resulting modification of inter-fiber bonding mechanisms (Bosco *et al*. 2016). Such interaction leads to significant changes in mechanical properties, dimensional stability, and failure mechanisms, which must be carefully considered in both modeling and optimization processes.

Moisture-Dependent Material Behavior

At the material level, the presence of moisture affects the internal structure of paper fibers, leading to swelling, softening, and a reduction in interfiber bonding strength (Cornaggia *et al*. 2023). These microstructural changes translate into a measurable decrease in macroscopic mechanical properties, including elastic modulus, compressive strength, and shear stiffness. Moisture gradients may also induce dimensional distortions and warping, which are relevant for both production control and structural performance assessment (Beck and Fischerauer 2022). The degree of degradation depends on the moisture content, fiber composition, manufacturing process, and the use of protective barrier coatings intended to reduce water uptake (Popil 2006; Fang *et al*. 2025; Wan *et al*. 2022).

In corrugated board, these effects are compounded by the layered structure of the material. Differences in moisture absorption between liners and the corrugated medium can lead to nonuniform deformation, internal stresses, and changes in load transfer mechanisms (Beck and Fischerauer 2022). As a result, even moderate variations in relative humidity may significantly alter the structural response of the system.

Influence on Structural Performance

Moisture-induced degradation has a direct impact on key performance metrics used in the design of corrugated structures (Cornaggia *et al*. 2023; Tworzydło *et al*. 2026). For example, reductions in compressive strength at the paper level lead to lower Edge Crush Test (ECT) values, which in turn affect the load-bearing capacity of boxes (Garbowski *et al*. 2021a; Garbowski and Andrzejak 2022; Desloges-Vullierme *et al*. 2008). Similarly, decreases in stiffness influence bending behavior, resulting in larger deflections and reduced resistance to buckling (Isaksson and Gradin 2009; Garbowski and Gajewski 2021).

Representative experimental and numerical studies indicate that the influence of humidity on corrugated board is not marginal but may dominate the structural response. Depending on the paper grade, board configuration, conditioning time, and test method, increasing relative humidity from standard laboratory conditions to high-humidity environments may lead to reductions of several tens of percent in stiffness-related properties and compressive strength indicators. In practical terms, this may translate into a noticeable decrease in ECT and BCT, increased bending deflections, lower critical loads, and a higher probability of local instability. These values should not be interpreted as universal correction factors, because the response depends on the sorption history, adhesive system, flute geometry, and layer composition. Nevertheless, they demonstrate that moisture-dependent degradation must be included whenever optimization targets real storage, transport, or service conditions rather than only standardized laboratory performance (Cornaggia *et al*. 2023; Tworzydło *et al*. 2026).

In addition to changes in stiffness and strength, moisture also affects failure modes (Cornaggia *et al*. 2023). Under dry conditions, failure may be governed by material strength, while in humid environments, instability phenomena such as local buckling or progressive crushing may become dominant (Gajewski *et al*. 2021; Mrówczyński and Garbowski 2023). This shift in failure mechanisms further complicates the prediction of structural performance.

The time-dependent nature of moisture transport introduces an additional layer of complexity. In real-world conditions, corrugated board structures are often exposed to varying humidity levels over time, leading to transient states that are not captured by standard laboratory tests. This dynamic behavior can result in delayed degradation or recovery of mechanical properties, depending on the environmental history (Cornaggia *et al*. 2023; Tworzydło *et al*. 2026).

Hygro-Mechanical Coupling in Modeling

Incorporating hygro-mechanical effects into modeling frameworks remains a significant challenge (Cornaggia *et al*. 2023). Many analytical and numerical models still assume constant material properties, which simplifies computation but limits their predictive capability under variable humidity and temperature. While such assumptions may be acceptable for short-term or controlled applications, they limit the applicability of these models in realistic scenarios.

More advanced approaches introduce moisture-dependent material properties through empirical degradation functions, which relate stiffness and strength parameters to moisture content or relative humidity (Cornaggia *et al*. 2023). These functions can be incorporated into finite element models or homogenization frameworks, enabling a more realistic representation of the structural response.

However, the accuracy of such models depends on the availability of reliable experimental data, which are often limited or scattered across different studies. Moreover, the coupling between moisture transport and mechanical response is inherently nonlinear and may require multiphysics modeling approaches, further increasing computational complexity.

Implications for Optimization

The strong sensitivity of corrugated board to environmental conditions has important implications for optimization-based design. In many existing studies, optimization is performed under fixed material properties, implicitly assuming constant environmental conditions. This approach may lead to designs that perform well under laboratory conditions but fail to meet requirements in real-world applications.

To address this issue, it is necessary to incorporate environmental variability into the optimization process. This can be achieved through robust or reliability-based optimization methods, which account for uncertainties in material properties and loading conditions. In such frameworks, design solutions are evaluated not only based on their nominal performance but also on their sensitivity to variations in environmental parameters (Cornaggia *et al*. 2023; Fitas *et al*. 2023).

Another important aspect is the selection of appropriate objective functions and constraints. For example, instead of optimizing stiffness or strength under a single set of conditions, it may be more relevant to consider worst-case scenarios or performance over a range of humidity levels (Cornaggia *et al*. 2023). This shift from deterministic to environment-aware design represents a key step toward more reliable and practical applications.

Challenges and Research Needs in Hygro-mechanical Effects

Despite its importance, the integration of hygro-mechanical effects into the design and optimization of corrugated board structures remains limited. Key challenges include the lack of standardized experimental data for moisture-dependent properties, difficulties in modeling coupled moisture–mechanical behavior, and the increased computational cost associated with multiphysics simulations.

Future research should focus on the development of consistent material models that capture the influence of moisture across different scales, from fiber-level interactions to structural response (Tworzydło *et al*. 2026). In addition, there is a need for efficient computational frameworks that enable the incorporation of environmental effects into optimization without prohibitive cost (Fitas 2025).

The combination of experimental studies, advanced modeling techniques, and data-driven approaches offers a promising pathway toward achieving this goal (Cornaggia *et al*. 2023). In the short term, the most important need is the development of reliable moisture-dependent material datasets and their use in validated mechanical models. In the longer term, such datasets may support surrogate models and condition-aware design tools, provided that their predictions are verified against independent experiments performed under controlled humidity and temperature conditions. Digital-twin concepts may eventually benefit from such datasets, but their use in corrugated board structural design should currently be regarded as a research perspective rather than an established design methodology.

CURRENT LIMITATIONS AND RESEARCH GAPS

Despite significant progress in the modeling and optimization of corrugated board structures, several limitations remain that hinder the development of fully reliable and performance-driven design methodologies. These challenges arise from both the intrinsic complexity of the material and the fragmented nature of existing research efforts.

Fragmentation of Modeling and Optimization Approaches

One of the most evident limitations is the lack of integration between modeling frameworks and optimization techniques. While advanced models, including finite element simulations and homogenization approaches, have been developed to describe the mechanical behavior of corrugated board, they are often used independently of optimization procedures (Aduke *et al*. 2023; Fitas *et al*. 2025). Conversely, optimization studies frequently rely on simplified or empirical models, which may not adequately capture the underlying physics (Biancolini and Brutti 2003).

This disconnect limits the practical applicability of optimization-based design, as high-fidelity models are rarely incorporated into iterative optimization loops due to their computational cost. As a result, there is a need for integrated frameworks that combine accurate modeling with efficient optimization strategies, enabling both reliability and computational feasibility.

Limited Consideration of Hygro-Mechanical Effects

Although the sensitivity of paper-based materials to environmental conditions is well recognized, its integration into structural modeling and optimization remains insufficient (Cornaggia *et al*. 2023). Most existing studies assume constant material properties, neglecting the effects of moisture and temperature on stiffness, strength, and failure behavior (Aduke *et al*. 2024).

Even when moisture-dependent properties are considered, they are typically introduced through simplified degradation functions that do not account for spatial variability or transient effects (Tworzydło *et al*. 2026). This limitation is particularly critical for real-world applications, where environmental conditions can vary significantly over time and space.

The absence of comprehensive hygro-mechanical models in optimization frameworks represents a major gap, as it may lead to designs that are not robust under realistic service conditions.

Insufficient Experimental Validation

Another important limitation is the relatively limited availability of high-quality experimental data for validating modeling and optimization approaches (Garbowski *et al*. 2021b; Aduke *et al*. 2024; Fitas *et al.* 2025). While standardized tests such as ECT and BCT provide useful performance indicators, they offer only indirect insight into the underlying mechanical behavior (Biancolini and Brutti 2003; Popil and Hojjatie 2010; Garbowski and Andrzejak 2022).

Detailed experimental studies, including full-field measurements and controlled environmental testing, are less common and often limited to specific configurations (Garbowski *et al*. 2021b; Cornaggia *et al*. 2023). This lack of comprehensive datasets makes it difficult to calibrate and validate advanced models, particularly those incorporating nonlinear behavior or multi-physics effects. Recent inverse identification approaches indicate that calibration can be significantly improved through combined structural testing and parameter reconstruction strategies (Garbowski *et al*. 2025b).

For model verification, priority should be given to a hierarchy of tests rather than to a single indicator. At the material level, tensile tests, SCT, and shear-related tests are needed to identify orthotropic paper properties. At the board level, ECT, four-point bending, torsion or transverse shear tests, and local buckling or crushing tests are required to validate equivalent stiffnesses and failure criteria. At the structural level, BCT remains essential for assessing global box performance. For environment-aware models, the same tests should be repeated after controlled humidity and temperature conditioning, because validation under standard climate alone is not sufficient for predicting service performance (Biancolini and Brutti 2003; Fitas *et al*. 2025; Cornaggia *et al*. 2023; ISO 3037; ISO 9895; ISO 12048; ISO 187; ASTM D642; ASTM D7030). Moreover, discrepancies between experimental setups and modeling assumptions can introduce additional uncertainty, further complicating the validation process.

Simplified Treatment of Failure Mechanisms

Failure mechanisms in corrugated board structures are complex and may involve a combination of local buckling, material crushing, delamination, and shear instability (Isaksson and Gradin 2009; Gajewski *et al*. 2021; Mrówczyński and Garbowski 2023; Ai *et al*. 2025). However, many existing models and optimization studies rely on simplified failure criteria, often based on global strength indicators or linear elastic assumptions (Biancolini and Brutti 2003).

Such simplifications may be acceptable for preliminary design but are insufficient for accurately predicting failure in more demanding applications. In particular, the interaction between different failure modes and the influence of imperfections are rarely captured in current frameworks (Mrówczyński *et al.* 2022a; Mrówczyński and Garbowski 2023). A more comprehensive treatment of failure mechanisms, including nonlinear and instability-driven phenomena, is therefore needed to improve the predictive capability of design models.

In addition to crushing and buckling, interface-related failure deserves particular attention. The bond between the liner and the corrugated medium governs load transfer, especially in bending, shear, impact, and post-buckling response. If this bond is weakened by humidity, manufacturing defects, ageing, or repeated loading, the effective stiffness and failure mode of the board may change substantially. Therefore, optimization frameworks based on perfect-bond assumptions should be used with caution when failure, durability, or service-life assessment is considered (Twede and Selke 2005; Cornaggia *et al*. 2023; Ai *et al*. 2025; Bian and Qing 2021).

Limited Use of Multi-Objective and Robust Optimization

Although corrugated board design inherently involves multiple competing objectives, many optimization studies focus on single-objective formulations, typically aiming to minimize material usage or maximize strength (Minakawa *et al*. 2025). This approach does not fully reflect the complexity of real design problems, where trade-offs between performance, cost, and environmental impact must be considered (Jannes *et al*. 2023; Kim *et al*. 2023).

In addition, the role of uncertainty is often neglected. Variability in material properties, manufacturing processes, and environmental conditions can significantly affect structural performance, yet these factors are rarely included in optimization formulations

(Cornaggia *et al*. 2023). As a result, the designs may lack robustness and may not perform reliably under real-world conditions.

Computational Challenges

The application of advanced modeling and optimization techniques is often limited by computational cost (Aduke *et al*. 2024). High-fidelity finite element models, particularly those incorporating nonlinear behavior or multiphysics coupling, require significant computational resources, making them impractical for large-scale optimization or real-time applications.

Table 4. Current Limitations in Optimization-Based Corrugated Board Design and Recommended Future Research Priorities

Limitation	Current Status	Consequence	Short-term Priority	Longer-term Direction
Limited experimental validation	Common	Low confidence in predictive models	Establish benchmark datasets for ECT, SCT, BCT, bending, shear, buckling, and crushing tests	Shared validation databases covering different board grades, geometries, and climates
Hygro-mechanical effects neglected	Frequent	Overestimated performance under service conditions	Add moisture-dependent material properties and controlled-humidity validation	Coupled moisture-transport and mechanical optimization frameworks
Simplified failure criteria	Frequent	Unsafe or non-conservative predictions	Refine criteria for crushing, buckling, shear instability, and interface failure	Progressive damage and multi-mode failure models
Interface damage and delamination poorly represented	Common	Incorrect load-transfer and failure prediction	Measure adhesive/interface stiffness and strength under different humidity levels	Cohesive-zone and degradation models integrated into homogenized frameworks
Expensive high-fidelity FEM	Significant	Poor efficiency in optimization loops	Use FEM as benchmark and data source for reduced models	Validated ROM/surrogate frameworks with uncertainty quantification
Single-objective optimization	Common	Suboptimal designs under competing requirements	Use Pareto-based strength-weight-cost formulations	Robust and reliability-based multi-objective optimization
Digital twins immature for corrugated board	Emerging	Risk of overstating practical readiness	Separate demonstrated data-driven tools from conceptual workflows	Sensor-driven, validated, condition-aware digital twins

While surrogate-based and reduced-order modeling approaches offer promising solutions, their development and validation require careful consideration, including the selection of appropriate training data and the management of approximation errors (Chaveesuk *et al*. 2021; Fitas 2025). Balancing accuracy and efficiency remains a key challenge in the development of practical optimization frameworks. The principal methodological gaps identified in the reviewed literature and their corresponding research priorities are summarized in Table 4 (Chaveesuk *et al*. 2021; Cornaggia *et al*. 2023; Fitas *et al*. 2023; Aduke *et al*. 2024; Fitas 2025; Ai *et al*. 2025; Twede and Selke 2005).

Lack of Standardized Design Frameworks

Finally, there is a lack of standardized methodologies for the optimization-based design of corrugated board structures. Existing approaches are often tailored to specific applications or research studies, with limited generalization to other contexts.

The absence of unified frameworks and guidelines makes it difficult to transfer knowledge between different domains, such as packaging, furniture, and construction (Smardzewski and Jasińska 2017; Suarez *et al*. 2021). Developing standardized approaches that integrate material characterization, modeling, and optimization would significantly enhance the accessibility and applicability of advanced design methods (Fitas *et al*. 2023).

FUTURE PERSPECTIVES

The evolution of corrugated board from a packaging material to a versatile structural medium opens new opportunities for the development of advanced, performance-driven design methodologies. While significant progress has been made in modeling and optimization, the field remains far from mature (Aduke *et al*. 2024). Future research is expected to focus on the integration of multiphysics modeling, data-driven approaches, and robust optimization frameworks, enabling more reliable and efficient use of corrugated structures in increasingly demanding applications (Garbowski and Karasiewicz 2026; Cornaggia *et al*. 2023; Chaveesuk *et al*. 2021; Fitas 2025).

For clarity, the future research directions can be divided into two groups. Short-term priorities concern improvements that can be implemented with currently available experimental and modeling tools, such as better validation, moisture-dependent material calibration, refined failure criteria, interface characterization, and benchmark comparisons between modeling approaches. Longer-term directions include robust optimization under uncertainty, hybrid physics-based and data-driven models, and digital-twin concepts supported by real-time sensing and model updating. This distinction is important because not all future directions have the same level of maturity or industrial readiness.

Integration of Hygro-Mechanical Effects into Design Frameworks

One of the most critical directions for future development is the systematic incorporation of environmental effects into modeling and optimization processes (Cornaggia *et al*. 2023). As demonstrated in previous sections, moisture and temperature significantly influence the mechanical behavior of corrugated board, yet their role is still insufficiently addressed in current design methodologies.

Future frameworks should aim to couple moisture transport models with mechanical analysis, enabling the prediction of time-dependent structural performance under realistic environmental conditions. This integration would allow for environment-aware optimization, where designs are evaluated not only under nominal conditions but across a range of possible scenarios. Such an approach is essential for applications in construction and long-term use, where environmental exposure is unavoidable (Smardzewski and Jasińska 2017; Tworzydło *et al*. 2026).

Development of Robust and Reliability-Based Optimization

The inherent variability of paper-based materials and the uncertainty associated with environmental conditions necessitate the adoption of robust and reliability-based optimization methods (Cornaggia *et al*. 2023). Instead of focusing solely on optimal performance under idealized conditions, future approaches should aim to identify designs that maintain acceptable performance despite variations in material properties, geometry, and loading (Fitas *et al*. 2023; Mrówczyński *et al*. 2022c).

This shift requires the integration of probabilistic models and uncertainty quantification techniques into the optimization process. Methods such as stochastic optimization, sensitivity analysis, and reliability assessment can provide valuable insight into the stability of design solutions and support the development of safer and more dependable structures.

Data-Driven and Machine Learning Approaches

The increasing availability of experimental and simulation data create new opportunities for the application of data-driven methods in the design of corrugated board structures. Machine learning techniques, including artificial neural networks and Gaussian process models, can be used to approximate complex relationships between design variables and performance metrics (Chaveesuk *et al*. 2021).

These approaches are particularly promising in the context of surrogate-based optimization, where they can significantly reduce computational cost while maintaining acceptable accuracy. In addition, machine learning methods enable inverse design strategies, in which desired performance characteristics are specified, and the corresponding structural configuration is determined automatically (Chaveesuk *et al*. 2021; Fitas 2025).

In comparison with classical optimization studies summarized in previous reviews, the main open issue is no longer only the selection of an optimization algorithm but the reliability of the model being optimized. For this reason, future data-driven approaches should report not only prediction accuracy but also the design space used for training, the physical meaning of input variables, the source of target data, and the limits of extrapolation. Hybrid physics-informed approaches may be particularly useful because they can combine the speed of surrogate prediction with constraints derived from mechanics, stability, and material behavior (Chaveesuk *et al*. 2021; Fitas 2025).

The integration of data-driven models with physics-based approaches represents a key direction for future research, combining the strengths of both methodologies to achieve improved predictive capabilities.

Digital Twin Concepts and Real-Time Design

Digital-twin concepts are promising but still immature in the specific context of corrugated board structural optimization. In general, a digital twin would require a virtual model of the board, box, or structural component that is updated using data from production, storage, transport, or service conditions. Such a framework could support condition-aware prediction of stiffness, strength, deformation, damage accumulation, or remaining load-bearing capacity. However, published applications in corrugated board design remain limited, and most current developments should be regarded as research perspectives rather than established industrial practice (Biancolini 2005b; Garbowski and Karasiewicz 2026).

A realistic digital-twin framework for corrugated board would require several components: reliable sensing of environmental and mechanical conditions, validated moisture-dependent material models, efficient reduced-order or surrogate models, uncertainty quantification, and experimental procedures for model updating. Until these components are available and validated, digital twins should be presented as a long-term direction rather than as a mature design method. In the near future, more practical progress may be expected from partial implementations, such as online quality control, image-based geometry identification, moisture-aware performance prediction, and surrogate-assisted design tools (Biancolini 2005b; Chaveesuk *et al*. 2021; Fitas 2025).

Advanced Material and Structural Design Concepts

Future developments may also involve the exploration of new material and structural concepts aimed at enhancing the performance of corrugated board, including advanced surface coatings improving hydrophobicity and thermal retention (Fang *et al.* 2025; Wan *et al*. 2022). These concepts include alternative flute geometries (Yuan *et al.* 2014b), hybrid material systems, functionally graded structures, and multifunctional coated boards with flame-retardant or hydrophobic performance (Wan *et al*. 2022; Fang *et al*. 2025). Broader corrugated-core engineering studies also indicate the potential of geometry-driven structural concepts beyond paperboard applications (Zhang *et al*. 2023).

The application of optimization techniques to such advanced configurations can lead to innovative solutions that go beyond the limitations of traditional designs. In particular, the combination of geometric optimization with material tailoring offers significant potential for improving both mechanical efficiency and sustainability (Jannes *et al*. 2023; Kim *et al*. 2023).

Towards Integrated Design Frameworks

Ultimately, the future of corrugated board design lies in the development of integrated frameworks that combine material characterization, multiscale modeling, and optimization within a unified environment. Such frameworks should be capable of handling complex interactions between design variables, performance metrics, and environmental conditions, while remaining computationally efficient and practically applicable (Cornaggia *et al.* 2023).

The integration of experimental data, advanced modeling techniques, and optimization algorithms into a coherent workflow would enable a shift from empirical design toward fully predictive and performance-based methodologies (Rodríguez and Vecchietti 2006; Rodríguez and Vecchietti 2008; Fitas *et al*. 2023), while also accounting for manufacturing-process effects such as localized deformation induced during printing and converting operations (Holmvall and Uesaka 2007).

Beyond structural sizing, optimization methods have also been applied to production planning and scheduling, ranging from earlier multiobjective genetic algorithms for cardboard-box manufacturing to recent evolutionary approaches for corrugated-board decision support (Misawa and Kanezashi 2005; Minakawa *et al*. 2025). Such methodologies should also increasingly incorporate logistics efficiency, cleaner production strategies, and sustainability criteria, since packaging optimization is inherently linked to transport performance and environmental impact (Duarte *et al.* 1998; Huo and Saito 2010).

Full-field experimental techniques such as digital image correlation also offer valuable opportunities for identifying constitutive parameters of fiber-based packaging materials, including lateral strain measures such as Poisson's ratios (Hua e*t al*. 2020).

Artificial intelligence-assisted workflows may further accelerate this transition by supporting rapid screening of design alternatives and adaptive parameter updating. Such a transition may ultimately determine whether corrugated board evolves from a packaging material into a fully engineered structural material (Garbowski 2024; Chaveesuk *et al*. 2021; Fitas 2025).

Overall, the reviewed methods can be arranged according to their current maturity. Empirical formulas, standardized tests, FEM, and homogenization-based shell or plate models are already established tools, although they still require careful calibration. Surrogate and machine-learning models are emerging tools whose reliability depends on dataset quality and validation. Digital twins and real-time adaptive design remain long-term research perspectives for corrugated board structures. Recognizing these different maturity levels prevents overstatement and helps define realistic research priorities. This maturity-based classification also clarifies the position of the present review with respect to earlier optimization-oriented surveys: the central question is not only how to search for an optimum, but how to ensure that the optimized response is mechanically meaningful, experimentally validated, and robust under realistic environmental conditions.

CONCLUSIONS

The present review shows that optimization-based design of corrugated board is moving from empirical strength estimation toward integrated, model-based and data-supported workflows. In contrast to broad reviews of optimization practices in the corrugated board industry, the emphasis here has been placed on the structural-mechanics foundation required for reliable optimization. The most mature tools are still standardized testing, analytical formulas, FEM, and homogenization-based models. However, their use in optimization remains limited by incomplete validation, simplified failure descriptions, insufficient representation of interface damage, and limited consideration of moisture-dependent behavior. Short-term progress should therefore focus on benchmark experimental datasets, controlled-humidity validation, refined criteria for buckling, crushing and delamination, and transparent comparison of modeling approaches. Longer-term development may involve robust optimization, surrogate-assisted workflows, machine learning, and digital twins, but these approaches require rigorous validation before they can be treated as reliable industrial design tools.

REFERENCES CITED

Aboura, Z., Talbi, N., Allaoui, S., and Benzeggagh, M. L. (2004). "Elastic behaviour of corrugated cardboard: Experiments and modeling," *Composite Structures* 63(1), 53-62. https://doi.org/10.1016/S0263-8223(03)00131-4

Aduke, R. N., Venter, M. P., and Coetzee, C. J. (2023). "An analysis of numerical homogenisation methods applied on corrugated paperboard," *Mathematical and Computational Applications* 28(2), article 46. https://doi.org/10.3390/mca28020046

Aduke, R. N., Venter, M. P., and Coetzee, C. J. (2024). "Numerical modeling of corrugated paperboard boxes," *Mathematical and Computational Applications* 29(4), article 70. https://doi.org/10.3390/mca29040070

Ai, X., Chen, B., and Kassapoglou, C. (2025). "Structural cohesive element for the modelling of delamination in composite laminates without the cohesive zone limit," *Engineering Fracture Mechanics* 329, article 111586. https://doi.org/10.1016/j.engfracmech.2025.111586

ASTM D642, "Standard test method for determining compressive resistance of shipping containers, components, and unit loads".

ASTM D4577, "Standard test method for compression resistance of a container under constant load".

ASTM D7030, "Standard test method for short term creep performance of corrugated fiberboard containers under constant load using a compression test machine".

Beck, M., and Fischerauer, G. (2022). "Modeling warp in corrugated board based on homogenization techniques for in-process measurement applications," *Applied Sciences* 12(3), article 1684. https://doi.org/10.3390/app12031684

Bian, P., and Qing, H. (2021). "A novel phase-field based cohesive zone model for modeling interfacial failure in composites," *Numerical Methods in Engineering* 122(23), 7054-7077. https://doi.org/10.1002/nme.6821

Biancolini, M. E. (2005a). "Evaluation of equivalent stiffness properties of corrugated board," *Composite Structures* 69(3), 322-328. https://doi.org/10.1016/j.compstruct.2004.07.014

Biancolini, M. E. (2005b). "Online quality control of corrugated board panel by image processing," *International Journal of Computer Applications in Technology* 23(2-4), 157-165. https://doi.org/10.1504/IJCAT.2005.006472

Biancolini, M. E., and Brutti, C. (2003). "Numerical and experimental investigation of the strength of corrugated board packages," *Packaging Technology and Science* 16(2), 47-60. https://doi.org/10.1002/pts.609

Bolat, A. (2000). "An extended scheduling model for producing corrugated boxes," *International Journal of Production Research* 38(7), 1579-1599. https://doi.org/10.1080/002075400188735

Bosco, E., Peerlings, R. H. J., and Geers, M. G. D. (2016). "Hygro-mechanical properties of paper fibrous networks through asymptotic homogenization and comparison with idealized models," *Mechanics of Materials* 108, 11-20. https://doi.org/10.1016/j.mechmat.2017.01.013

Cáceres-Naranjo, D., González, P., Pérez, M., and Calvo, S. (2024). "Enhancing packaging design for dynamic loads: A methodological approach for corner impact situations in packaging," *Packaging Technology and Science* 37(11), 1085-1094. https://doi.org/10.1002/pts.2843

Chaveesuk, R., Santichiwasatiana, B., and Jinkarn, T. (2021). "Prediction using artificial neural networks of edgewise compression strength of corrugated fiberboards," *Agriculture and Natural Resources* 55(6), 1062-1071. https://doi.org/10.34044/J.ANRES.2021.55.6.17

Cornaggia, A., Gajewski, T., Knitter-Piątkowska, A., and Garbowski, T. (2023). "Influence of humidity and temperature on mechanical properties of corrugated board—Numerical investigation," *BioResources* 18(4), 7490-7509. https://doi.org/10.15376/biores.18.4.7490-7509

Cornaggia, A., Mrówczyński, D., Gajewski, T., Knitter-Piątkowska, A., and Garbowski, T. (2024). "Advanced numerical analysis of transport packaging," *Applied Sciences*

14(24), article 11932. https://doi.org/10.3390/app142411932
Desloges-Vullierme, I., Chaussy, D., Serra-Tosio, J.-M., Schott, S., and Mauret, E. (2008). "Predicting the compressive property of a corrugated medium," *Cellulose Chemistry and Technology* 42(1-3), 71-80.
Duarte, E. A., Neto, I., Alegrias, M., and Barroso, R. (1998). "Appropriate technology for pollution control in corrugated board industry – The Portuguese case," *Water Science and Technology* 38(6), 45-53. https://doi.org/10.1016/S0273-1223(98)00595-2
Fang, Y., Chen, J., Lin, C., Sun, H., and Chen, Y. (2025). "Study on the preparation of hollow silica nanospheres and their heat retention and hydrophobicity in paperboard coatings," *Packaging Technology and Science* 38(4), 283-292. https://doi.org/10.1002/pts.2872
Fitas, R. (2025). "Modeling the effective elastic modulus and thickness of corrugated boards using Gaussian process regression and expected hypervolume improvement," *Lecture Notes in Civil Engineering* 650, 69-80. https://doi.org/10.1007/978-3-031-92754-6_7
Fitas, R., Schaffrath, H. J., and Schabel, S. (2023). "A review of optimization for corrugated boards," *Sustainability* 15(21), article 15588. https://doi.org/10.3390/su152115588
Fitas, R., Schaffrath, H. J., and Schabel, S. (2025). "On the design of corrugated boards: A new FEM modeling and experimental validation," *TAPPI Journal* 24(8), 406-418. https://doi.org/10.32964/TJ24.8.406
Gajewski, T., Garbowski, T., Staszak, N., and Kuca, M. (2021). "Crushing of double-walled corrugated board and its influence on the load capacity of various boxes," *Energies* 14(14), article 4321. https://doi.org/10.3390/en14144321
Gao, D., and Lu, F.-D. (2013). "Nonlinear dynamic analysis of series cushioning system made with expanded polyethylene and corrugated paperboard," *Advances in Mechanical Engineering* 2013, article 816951. https://doi.org/10.1155/2013/816951
Garbowski, T. (2024). "Revolutionizing corrugated board production and optimization with artificial intelligence," *BioResources* 19(2), 2003-2006. https://doi.org/10.15376/biores.19.2.2003-2006
Garbowski, T. (2025). "Review on numerical homogenization of corrugated materials," *BioResources* 20(2), 5157-5184. https://doi.org/10.15376/biores.20.2.Garbowski
Garbowski, T., and Andrzejak, K. (2022). "From paper to corrugated board - modeling the edge crush test," *Przegląd Papierniczy* 78(5), 271-277. https://doi.org/10.15199/54.2022.5.1
Garbowski, T., and Borecki, P. (2025). "Analysis of the impact of futuristic corrugated layer shape on mechanical properties and cost of single-wall corrugated board," *Przegląd Papierniczy* 80(11), 271-277. https://doi.org/10.15199/54.2024.11.1
Garbowski, T., and Borysiewicz, A. (2014). "The stability of corrugated board packages," *Przegląd Papierniczy* 70(8), 452-458.
Garbowski, T., Cornaggia, A., Gajewski, T., Grabski, J. K., and Mrówczyński, D. (2025a). "Inverse-based multi-step numerical homogenization for mechanical characterization of converted corrugated board," *Composite Structures* 373, article 119701. https://doi.org/10.1016/j.compstruct.2025.119701
Garbowski, T., and Gajewski, T. (2021). "Determination of transverse shear stiffness of sandwich panels with a corrugated core by numerical homogenization," *Materials* 14(8), article 1976. https://doi.org/10.3390/ma14081976
Garbowski, T., Gajewski, T., Grabski, J. K., Mrówczyński, D., and Cornaggia, A.

(2025b). "Identification of material and structural parameters of corrugated board in production and converting processes," *Advanced Structured Materials* 231, 127-139. https://doi.org/10.1007/978-3-031-84379-2_10

Garbowski, T., Gajewski, T., Mrówczyński, D., and Jędrzejczak, R. (2021a). "Crushing of single-walled corrugated board during converting: Experimental and numerical study," *Energies* 14(11), article 3203. https://doi.org/10.3390/en14113203

Garbowski, T., and Jarmuszczak, M. (2014a). "Homogenization of corrugated board: Part 2, numerical homogenization," *Przegląd Papierniczy* 70(7), 390-394.

Garbowski, T., and Jarmuszczak, M. (2014b). "Homogenization of corrugated paperboard: Part 1, analytical homogenization," *Przegląd Papierniczy* 70(6), 345-349.

Garbowski, T., and Jarmuszczak, M. (2014c). "Numerical strength estimate of corrugated board packages: Part 1, theoretical assumptions in numerical modeling of paperboard packages," *Przegląd Papierniczy* 70(4), 219-222.

Garbowski, T., and Jarmuszczak, M. (2014d). "Numerical strength estimate of corrugated board packages: Part 2, experimental tests and numerical analysis of paperboard packages," *Przegląd Papierniczy* 70(5), 277-281.

Garbowski, T., and Karasiewicz, D. (2026). "Digital twin of corrugated board packaging: Is it already feasible?," *Przegląd Papierniczy* 82(4), 187-195. https://doi.org/10.15199/54.2026.4.1

Garbowski, T., Knitter-Piątkowska, A., and Marek, A. (2021b). "New edge crush test configuration enhanced with full-field strain measurements," *Materials* 14(19). https://doi.org/10.3390/ma14195768

Garbowski, T., Knitter-Piątkowska, A., and Mrówczyński, D. (2021c). "Numerical homogenization of multi-layered corrugated board with creasing or perforation," *Materials* 14(14), article 3786. https://doi.org/10.3390/ma14143786

Garbowski, T., and Marek, A. (2014). "Homogenization of corrugated boards through inverse analysis," *OPT-i 2014 – 1st International Conference on Engineering and Applied Sciences Optimization, Proceedings*, pp. 1751-1766.

Garbowski, T., Szymczak-Graczyk, A., and Cornaggia, A. (2025c). "Sectional homogenization with a general nonlinear constitutive law for corrugated board analysis," *UNCECOMP Proceedings* 2025, 399-407. https://doi.org/10.7712/120225.12365.21479

Garg, A., Yadama, V., and Cofer, W. F. (2014). "Optimization of sandwich panel parameters for enhanced structural performance using homogenization methodology," *Proceedings of the American Society for Composites – 29th Technical Conference; 16th US-Japan Conference on Composite Materials; ASTM-D30 Meeting*.

Glasenapp, A. O., Edholm, B., and Drotz, M. (2010). "Model pack: The corrugated box prediction tool," *International Paper Board Industry* 53(4), 6.

Heposalmi, S., Matthews, S., Leminen, V., Varis, J., and Toghyani, A. (2022). "FEM as a package design tool for corrugated paperboard," *Procedia CIRP* 109, 610-616. https://doi.org/10.1016/j.procir.2022.05.302

Holmvall, M. (2022). "Predicting creep lifetime performance in edgewise compression of containerboards and for stacked corrugated board boxes," *Packaging Technology and Science* 35(1), 53-67. https://doi.org/10.1002/pts.2607

Holmvall, M., and Uesaka, T. (2007). "Nip mechanics of flexo post-printing on corrugated board," *Journal of Composite Materials* 41(17), 2129-2145. https://doi.org/10.1177/0021998307074135

Hua, G., Yang, M., Fei, W., and Lu, F. (2020). "Poisson's ratios of molded pulp materials by digital image correlation method and uniaxial tensile test," *Journal of Engineered Fibers and Fabrics* 15, article 1558925020908271. https://doi.org/10.1177/1558925020908271

Huang, D., Gao, D., and Lu, F. (2012). "The constitutive modeling of double-B flute corrugated board," *Applied Mechanics and Materials* 101-102, 1147-1150. https://doi.org/10.4028/www.scientific.net/AMM.101-102.1147

Huo, L., and Saito, K. (2010). "Sustainability assessment for optimizing logistics-oriented protective packaging design," *Journal of Packaging Science and Technology* 19(3), 203-214.

Imai, M., Tsuchikawa, K., and Sano, E. (2010). "Corrugated conductive paper for electromagnetic absorbers," *German Microwave Conference Digest of Papers (GeMIC 2010)*, 239-242.

Isaksson, P., and Gradin, P. (2009). "Shear buckling in the core of a corrugated board structure," *Composite Structures* 88(4), 610-614. https://doi.org/10.1016/j.compstruct.2008.06.014

ISO 187, "Paper, board and pulps — Standard atmosphere for conditioning and testing and procedure for monitoring the atmosphere and conditioning of samples".

ISO 1924-2:2008, "Paper and board — Determination of tensile properties. Part 2: Constant rate of elongation method (20 mm/min)".

ISO 3037:2022, "Corrugated fibreboard — Determination of edgewise crush resistance (non-waxed edge method)".

ISO 5628:2019, "Paper and board — Determination of bending stiffness — General principles for two-point, three-point and four-point methods".

ISO 9895:2008, "Paper and board — Compressive strength — Short-span test".

ISO 12048:1994, "Packaging — Complete, filled transport packages — Compression and stacking tests using a compression tester".

Jannes, R., Vanhauwermeiren, P., Slaets, P., and Juwet, M. (2023). "Assessing the sustainable potential of corrugated board-based bundle packaging of PET bottles: A life cycle perspective—A case study," *Clean Technologies* 5(4), 1214-1234. https://doi.org/10.3390/cleantechnol5040061

Johnson, S., Kang, L., Ou, H., Qaiser, Z., and Macort, J. (2019). "Automated box buckling strength analyses with finite element modeling," *Lecture Notes in Electrical Engineering* 543, 660-665. https://doi.org/10.1007/978-981-13-3663-8_89

Kim, S., Horvath, L., Park, J., and Russell, J. D. (2022). "Investigating the environmental benefits of increasing the pallet top deck stiffness in unit load system," *Proceedings of the 23rd IAPRI World Conference on Packaging*, 403-417.

Kim, S., Horvath, L., Russell, J. D., and Park, J. (2021). "Investigation of the effect of pallet top-deck stiffness on corrugated box compression strength as a function of multiple unit load design variables," *Materials* 14(21), article 6613. https://doi.org/10.3390/ma14216613

Kim, S., Horvath, L., Russell, J. D., and Park, J. (2023). "Sustainable and secure transport: Achieving environmental impact reductions by optimizing pallet-package strength interactions during transport," *Sustainability* 15(17), article 12687. https://doi.org/10.3390/su151712687

Kubera, H., and Tyczyński, P. (2009). "Volume optimization of transport packages made of corrugated board on the basis of the shape of unit package," *Przegląd Papierniczy* 65(7), 403-406.

Kumbhar, S. T., Kale, P. R., Chaudhari, S. H., Mune, S. G., and Pingale, A. D. (2025). "Virtual drop test analysis of corrugated box packaging for material handling," *Journal of Mines, Metals and Fuels* 73(3), 545-554. https://doi.org/10.18311/jmmf/2025/47425

Luong, V. D., Abbès, F., Abbès, B., Duong, P. T. M., Nolot, J.-B., Erre, D., and Guo, Y.-Q. (2018). "Finite element simulation of the strength of corrugated board boxes under impact dynamics," *Lecture Notes in Mechanical Engineering* Part F3, 369-380. https://doi.org/10.1007/978-981-10-7149-2_25

Mansour, K. M., Khedr, F., Elkassaby, Y. H., and Salem, A. H. (2024). "Waste minimization in corrugated sheets manufacturing: A statistical approach for optimal operating conditions," *Proceedings of the 6th Novel Intelligent and Leading Emerging Sciences Conference (NILES 2024)*, 397-402. https://doi.org/10.1109/NILES63360.2024.10753186

Minakawa, I., Kawakami, S., Miyashita, H., Fujio, T., Iida, T., and Sato, H. (2025). "Corrugated board production planning via multi-objective evolutionary optimization with variable dependency-based variation," *IEEE Access* 13, 181704-181718. https://doi.org/10.1109/ACCESS.2025.3623148

Misawa, H., and Kanezashi, M. (2005). "Multiple objective genetic algorithms approach to a cardboard box production scheduling problem," *Journal of Japan Industrial Management Association* 56(2), 74-83.

Mrówczyński, D., and Garbowski, T. (2023). "Influence of imperfections on the effective stiffness of multilayer corrugated board," *Materials* 16(3), article 1295. https://doi.org/10.3390/ma16031295

Mrówczyński, D., Knitter-Piątkowska, A., and Garbowski, T. (2022a). "Numerical homogenization of single-walled corrugated board with imperfections," *Applied Sciences* 12(19), article 9632. https://doi.org/10.3390/app12199632

Mrówczyński, D., Knitter-Piątkowska, A., and Garbowski, T. (2022b). "Optimal design of double-walled corrugated board packaging," *Materials* 15(6), article 2149. https://doi.org/10.3390/ma15062149

Mrówczyński, D., Knitter-Piątkowska, A., and Garbowski, T. (2022c). "Non-local sensitivity analysis and numerical homogenization in optimal design of single-wall corrugated board packaging," *Materials* 15(3), article 720. https://doi.org/10.3390/ma15030720

Park, J., Kim, G., Kwon, S., Chung, S., Kwon, S., Choi, W., Mitsuoka, M., Inoue, E., Okayasu, T., and Choe, J. (2012). "Finite element analysis of corrugated board under bending stress," *Journal of the Faculty of Agriculture, Kyushu University* 57(1), 181-188. https://doi.org/10.5109/22070

Popil, R. E. (2006). "Optimizing water resistance of linerboard coatings using pigments," *TAPPI Journal* 5(9), 18-26.

Popil, R. E., and Hojjatie, B. (2010). "Effects of component properties and orientation on corrugated container endurance," *Packaging Technology and Science* 23(4), 189-202. https://doi.org/10.1002/pts.889

Rodríguez, A., and Vecchietti, A. (2006). "MINLP and MILP optimization models for solving the cutting stock problem in the corrugated board boxes industry," *Proceedings of the XXII Interamerican Congress of Chemical Engineering (CIIQ 2006) and V Argentinian Congress of Chemical Engineering (CAIQ 2006)*.

Rodríguez, M. A., and Vecchietti, A. (2008). "Enterprise optimization for solving an assignment and trim-loss non-convex problem," *Computers and Chemical*

Engineering 32(11), 2812-2822. https://doi.org/10.1016/j.compchemeng.2007.09.004
Rodriguez, M. A., and Vecchietti, A. (2013). "Integrated planning and scheduling with due dates in the corrugated board boxes industry," *Industrial and Engineering Chemistry Research* 52(2), 847-860. https://doi.org/10.1021/ie302109j
Smardzewski, J., and Jasińska, D. (2017). "Mathematical models and experimental data for HDF-based sandwich panels with dual corrugated lightweight core," *Holzforschung* 71(3), 265-273. https://doi.org/10.1515/hf-2016-0146
Suarez, B., Muneta, L. M., Romero, G., and Sanz-Bobi, J. D. (2021). "Efficient design of thin wall seating made of a single piece of heavy-duty corrugated board," *Materials* 14(21), article 6645. https://doi.org/10.3390/ma14216645
Sun, J., Shan, C., Xu, Z., and Kun, L. (2024). "Corrugation parameters and mechanical performance of corrugated shells under the same weight and volume," *International Journal of Solids and Structures* 300, article 112918. https://doi.org/10.1016/j.ijsolstr.2024.112918
Talbi, N., Batti, A., Ayad, R., and Guo, Y. Q. (2009). "An analytical homogenization model for finite element modeling of corrugated board," *Composite Structures* 88(2), 280-289. https://doi.org/10.1016/j.compstruct.2008.04.008
Twede, D., and Selke, S. E. M. (2005). *Cartons, Crates and Corrugated Board: Handbook of Paper and Wood Packaging Technology*, DEStech Publications, Lancaster, PA. https://doi.org/10.1002/pts.688
Tworzydło, J., Piotrowska, E., Smagacz, R., Mrówczyński, D., Pyś, D., Gajewski, T., and Garbowski, T. (2026). "Corrugated board packaging with innovative design for enhanced durability during transport," *BioResources* 21(1), 2229-2253. https://doi.org/10.15376/biores.21.1.2229-2253
Viguié, J., and Dumont, P. J. J. (2013). "Analytical post-buckling model of corrugated board panels using digital image correlation measurements," *Composite Structures* 101, 243-254. https://doi.org/10.1016/j.compstruct.2013.01.023
Wan, C., Cheng, J., Yang, X., Fu, X., Ma, L., Xu, C., and Chen, Y. (2022). "Preparation of flame retardant hydrophobic renewable composite paperboard and its mechanical properties," *Acta Materiae Compositae Sinica* 39(5), 2201-2214. https://doi.org/10.13801/j.cnki.fhclxb.20210702.003
Wang, D. (2011a). "Compressive constitutive relation for multi-layer corrugated boards," *Applied Mechanics and Materials* 80-81, 365-369. https://doi.org/10.4028/www.scientific.net/AMM.80-81.365
Wang, X., and Jiang, C. (2024). "Stress extreme value optimization solution for infinitely corrugated core sandwich panel with circular opening under uniaxial tension," *Chinese Journal of Ship Research* 19(5), 158-165. https://doi.org/10.19693/j.issn.1673-3185.03369
Yuan, W., Xu, W., Zhang, G., and Xie, L. (2013). "The finite element study of the compressive strength of typical waveform corrugated box," *Applied Mechanics and Materials* 262, 390-394. https://doi.org/10.4028/www.scientific.net/AMM.262.390
Yuan, W., Sun, J. X., Zhang, G. M., Liao, D. Z., and Wang, Y. J. (2014a). "Corrugated board UV flute-shaped structure size optimization design based on the finite element," *Applied Mechanics and Materials* 469, 213-216. https://doi.org/10.4028/www.scientific.net/AMM.469.213
Yuan, W., Zhang, G. M., Liao, D. Z., and Liu, J. (2014b). "Corrugated board flute-shaped finite element analysis and optimization," *Applied Mechanics and Materials* 477-478, 1205-1209. https://doi.org/10.4028/www.scientific.net/AMM.477-478.1205

Zhang, J., Wang, L., Peng, D., Wang, T., Xie, Y., Li, J., Wang, C., Qiu, R., and Gao, Q. (2023). "Crashworthiness optimization of a sandwich tube filled with CFRP sinusoidal corrugated board," *Aerospace Science and Technology* 132, article 108065. https://doi.org/10.1016/j.ast.2022.108065

Zhang, Z., Qiu, T., Song, R., and Sun, Y. (2014). "Nonlinear finite element analysis of the fluted corrugated sheet in the corrugated cardboard," *Advances in Materials Science and Engineering* 2014, article 654012. https://doi.org/10.1155/2014/654012

Zhou, T.-M., and Chen, F.-F. (2009). "Computation method of equivalent elastic constants of corrugated board with multi-step homogenization," *Journal of Wuhan University of Technology* 31(17), 141-144. https://doi.org/10.3963/j.issn.1671-4431.2009.17.039

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